NAVRAMP TECHNICAL MANUAL

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Prepared for

NAVAL FACILITIES ENGINEERING COMMAND, PACIFIC

Environmental Compliance Product Line

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ABBREVIATIONS AND ACRONYMS

ACH	air changes per hour
ASD	active soil depressurization
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASTM	American Society for Testing and Materials
BWD	block wall depressurization
cfm	cubic foot per minute
CRM	continuous radon monitor
DOAS	dedicated outdoor air system
DOE	US Department of Energy
DON	Department of the Navy
DP	differential pressure
EPA	US Environmental Protection Agency
ERV	energy recovery ventilation
ft	foot
h	hour
h^{-1}	per hour
HAC	heating and air-conditioning
HEPA	high-efficiency particulate air
HVAC	heating, ventilating, and air-conditioning
L	liter
LFE	lateral field extension
MERV	minimum efficiency reporting value
NAVRAMP	Navy Radon Assessment and Mitigation Program
O&M	operation and maintenance
pCi	picocurie
pCi/h	picocurie per hour
pCi/L	picocurie per liter
PFET	pressure field extension test
PVC	polyvinyl chloride
RH	relative humidity
ROI	radius of influence
RPC	radon potential category
RRNC	radon-resistant new construction
SAM	supplemental air makeup
SCIF	Sensitive Compartmented Information Facility
SMD	submembrane depressurization
SP	shell pressurization
SPT	subslab permeability test
SSD	subslab depressurization
UFC	Unified Facilities Criteria
UFGS	Unified Facilities Guide Specification
USMC	US Marine Corps
WHO	World Health Organization

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1. INTRODUCTION

The intent of this document is to assist US Navy US Marine Corps (USMC) installations with the implementation of the Navy Radon Assessment and Mitigation Program (NAVRAMP). This is a technical document designed specifically to complement the *Navy Radon Assessment and Mitigation Program Guidebook for Naval Shore Installations* (US Navy 2021) and provides more detailed background information, the rationale for specific NAVRAMP policies and guidelines and lessons learned.

1.1 WHAT IS RADON

Radon is a naturally occurring, odorless, colorless, radioactive gas caused by the breakdown of uranium. Because uranium is a common chemical element found in soil and rock matrixes throughout the world (on average about 3 g of natural uranium per ton), detectable quantities of radon can be measured everywhere. Within certain rock formations (limestone, granite, shale, phosphate, and pitchblende), higher levels of uranium and its decay product radon are present. When radon is generated, it immediately begins diffusing toward the surface. In the outdoors, radon rarely reaches concentrations of concern; however, within enclosed spaces, such as buildings, radon can accumulate to levels more than federally mandated exposure limits for radiation workers (CFR 29 1910.1096[b]). Because these geological formations are common within the United States and worldwide, measurable quantities of radon have been detected and reported in all 50 states and in most countries as well. In fact, the US Environmental Protection Agency (EPA) has estimated that 1 in every 15 homes has elevated radon levels (EPA September 1994, A Citizen's Guide to Radon, Fourth Edition). Because of the prevalence of indoor elevated radon levels, radon exposure represents over half of the average annual radiation exposure for the typical US citizen and most people worldwide (Figure 1, WHO 2009). Currently the EPA has set an action level of any result ≥4 pCi/L (EPA May 2012, EPA 402-K-12-002).

Unlike the risks associated with lead-based paint or asbestos, the risk from radon exposure can never be removed—it can only be managed by taking appropriate measures. The only way to avoid the lung cancer risk from radon exposure is to test and, if appropriate, mitigate. If mitigation is required, diligence in the form of inspection, maintenance, and periodic retesting is essential to ensure long-term risk reduction.

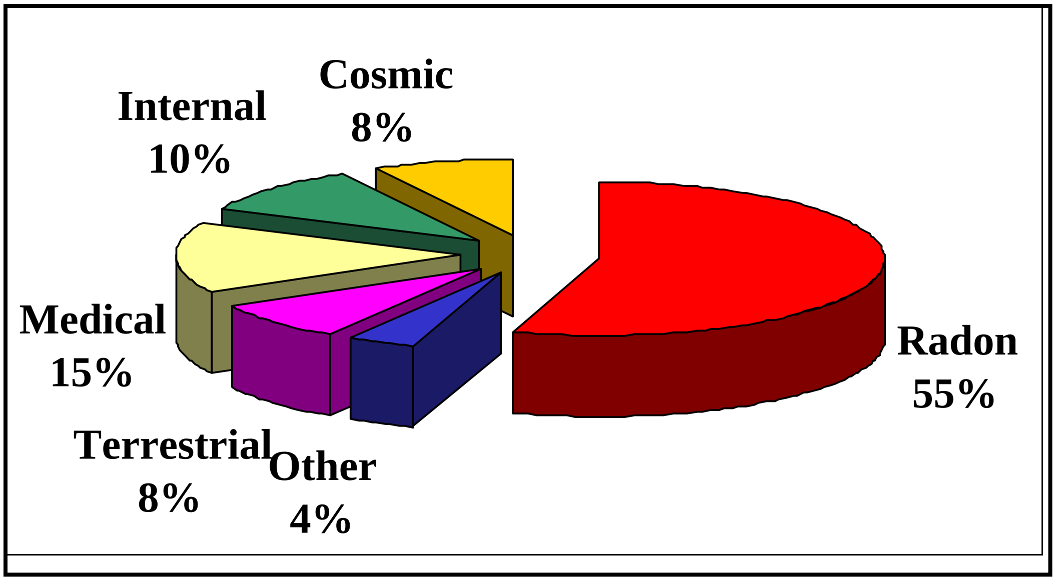
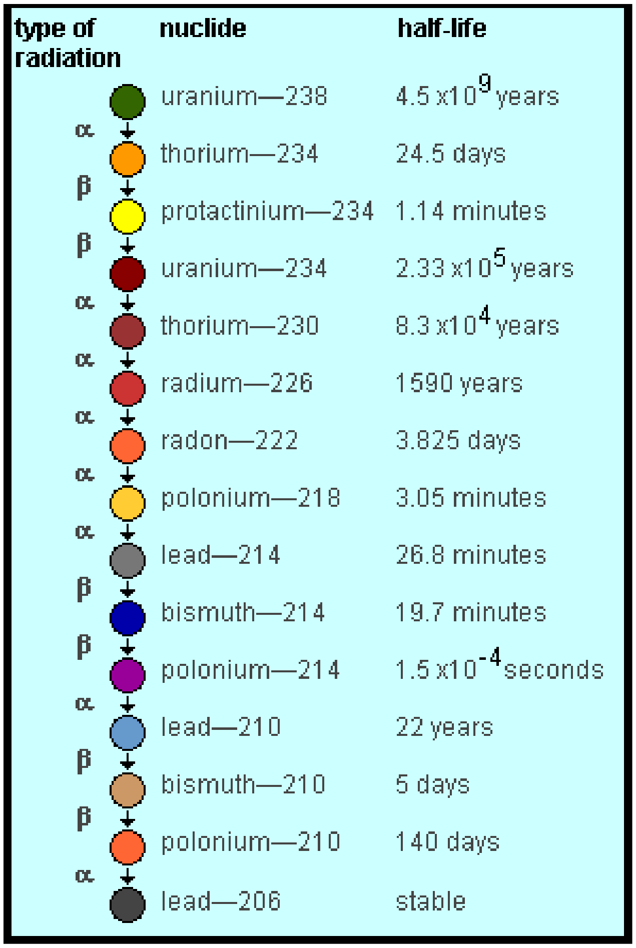


Figure 1. Sources of radiation exposure for the average US citizen.

1.1.1 The Isotopes of Radon

There are 33 known isotopes of radon; however only 2 [radon-220 (^{220}Rn) and radon-222 (^{222}Rn) are typically found indoors. Radon-220, typically called thoron, comes from the thorium-232 (^{232}Th) decay chain and is also a common substituent found in soil and rock matrixes throughout the world. Because of its short half-life (55.6 seconds) radon's diffusion potential through soil and rock is limited; and if it is found indoors at any appreciable concentration, it is usually linked to a source inside the building (e.g., water supply or building material). The other isotope, ^{222}Rn which is part of the uranium-238 decay chain (Figure 2) has a radioactive half-life of 3.82 days, which does allow it sufficient time to diffuse from its matrix and come into contact with building components that contact the soil. For this reason, ^{222}Rn is considered the primary isotope responsible for the radiation dose throughout the world (WHO 2009).

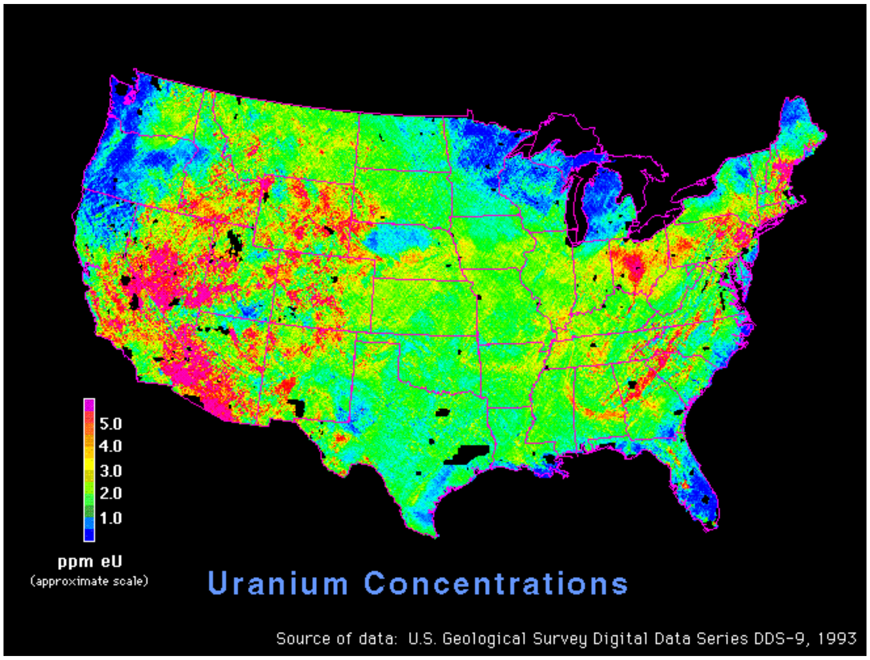


type of radiation	nuclide	half-life
	uranium—238	4.5 x10^{9} years
α		
	thorium—234	24.5 days
β		
	protactinium—234	1.14 minutes
β		
	uranium—234	2.33 x10^{5} years
α		
	thorium—230	8.3 x10^{4} years
α		
	radium—226	1590 years
α		
	radon—222	3.825 days
α		
	polonium—218	3.05 minutes
α		
	lead—214	26.8 minutes
β		
	bismuth—214	19.7 minutes
β		
	polonium—214	1.5 x10^{-4} seconds
α		
	lead—210	22 years
β		
	bismuth—210	5 days
β		
	polonium—210	140 days
α		
	lead—206	stable

Figure 2. The uranium decay series.

1.2 RADON AND GEOLOGY

In 1995, the US Geological Survey (USGS) in cooperation with EPA published a series of reports (USGS 1993, Open File Reports 93-292-A through K) that generalized radon potential within specific EPA regions. The evaluation and conclusions were based upon available USGS geological data and soil survey data collected by the Soil Conservation Service and included radon data collected by EPA during the 1986–1987 national residential radon survey. Practically speaking, one would expect that a precursor for indoor elevated radon levels would be the presence of appreciable amounts of surface uranium concentrations (Figure 3). Although the correlation was good between high indoor radon levels and significant levels of uranium and thorium in the soil, it was noted that similar levels of radon were also found in areas of the country with only trace levels of these elements. In addition, some areas that were known radiological "hot spots" exhibited a significantly lower than expected percentage of buildings with elevated radon levels. After further review and study, the conclusion was reached that the geologic radon potential was only part of predicting radon levels in a particular area. Factors such as the type and state of the geological formation (e.g., solid, layered, or fractured); local building codes; soil moisture content, depth, and permeability; and weather all played a contributing role. Therefore, in 1993, the EPA and USGS included with the release of the radon potential map a disclaimer that the map should not be used as an indicator whether to test and recommended that all homes and buildings be tested regardless of geographic location.



Uranium Concentrations

Source of data: U.S. Geological Survey Digital Data Series DDS-9, 1993

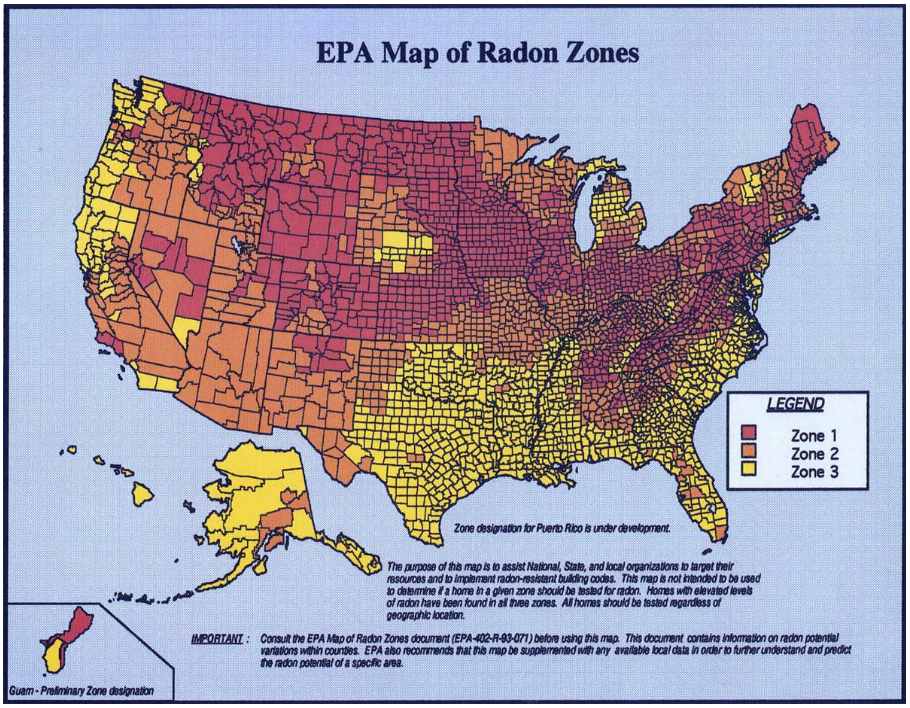
Figure 3. Uranium concentrations within the United States.

1.2.1 National Radon Potential Map

In the early 1980s, little was understood about the mechanisms of radon transport and its retention inside buildings. The key assumption made at that time was that for a building to have an indoor radon problem, a significant uranium source needed to be close at hand. It was therefore postulated that a radiological potential map showing uranium deposits would greatly assist in identifying areas of the United States that would require radon testing. Limited studies conducted in Colorado and Pennsylvania in the mid-1980s tended to support this hypothesis. However, these studies were performed mostly in areas with high levels of uranium covered with moderately to highly permeable soils. Because of this assumed correlation between geology and radon potential, the Indoor Radon Abatement Act (IRAA) of 1988 (Public Law 100-551a and b, Sections 307 and 309) directed the EPA to identify areas of the United States and its territories that have the potential to produce harmful levels of indoor radon. These characterizations were to be based on both geological data and indoor radon levels in homes and other structures. To assist with the geological requirements of the law, EPA entered into an Interagency Agreement with the USGS. From 1989 through 1992, EPA and USGS reviewed existing radiological maps, performed radon and geological surveys, and summarized all available radon data sets. The culmination of this effort was the publication in 1993 of the first EPA Map of Radon Zones (a more recent updated edition of the map is shown in Figure 4 and can be downloaded at https://www.epa.gov/radon/epa-map-radon-zones). On the radon map, each county was placed into one of 3 categories:

- Zone 1 High Potential (red): counties that have a predicted average indoor radon concentration >4 picocuries per liter (pCi/L).
- Zone 2 Moderate Potential (orange): counties that have a predicted average indoor radon concentration between 2 and 4 pCi/L.
- Zone 3 Low Potential (yellow): counties that have a predicted average indoor radon concentration <2 pCi/L.

A common misunderstanding by the public and others in interpreting the map was the use of the word "average," which brought into question the need to test buildings in Zone 2 and 3 counties. Later, EPA clarified the meaning of "average" to mean that if all the homes in this county were tested, the average results of all the homes tested would be expected to fall within those ranges. In addition, EPA stated that some homes in Zone 2 and 3 counties would test >4 pCi/L, and **the only way to know the radon level of a particular building or home is to test.**



The purpose of this map is to assist National, State, and local organizations to target their resources and to implement radon-resistant building codes. This map is not intended to be used to determine if a home in a given zone should be tested for radon. Homes with elevated levels of radon have been found in all three zones. All homes should be tested regardless of geographic location.

IMPORTANT : Consult the EPA Map of Radon Zones document (EPA-402-R-93-071) before using this map. This document contains information on radon potential variations within counties. EPA also recommends that this map be supplemented with any available local data in order to further understand and predict the radon potential of a specific area.

Figure 4. United States radon potential map.

1.2.2 Radon Emanation within Rock and Soil

Radon is a naturally occurring, odorless, colorless, radioactive gas caused by the breakdown of uranium. In nature, uranium is found in varying amounts throughout the earth's crust, primarily in the mineral form of tyuyamunite [$Ca(UO_2)_2(VO_4)_2 \cdot 6(H_2O)$]. However, certain rock formations—primarily light-colored volcanic rocks, granites, dark shales, sedimentary rocks that contain phosphate, and metamorphic rocks derived from these rocks—contain higher than average uranium content [e.g., >3 parts per million (ppm) of natural uranium per ton]. Because soil is essentially weathered rock mixed with organic matter, tyuyamunite is also found in soil at the same concentration as in the rock from which the soil was derived.

Because radon is a gas, it has much greater mobility than uranium and radium, which are fixed in the solid matrix of rocks and soils. For radon to be a concern, it has to migrate (diffuse or flow) from the rock or soil and become entrapped within a building. The term "radon emanation efficiency" refers to the overall ease with which radon moves from its natural matrix into the environment by a diffusion and/or flow mechanism. This efficiency is dependent upon the density of the matrix, the degree of fracture, the size of the pore spaces between the grains, and the moisture content. In addition, the efficiency is time-sensitive, because the most common isotope of indoor radon (^{222}Rn) has a relatively short half-life of 3.8 days. Therefore, in most cases, if radon is going to make a measurable contribution to the indoor levels, it must escape from the matrix and enter the building within fewer than five half-lives (USGS 1988, *Relationships Between Geology, Equivalent Uranium Concentration, and Radon in Soil Gas, Fairfax County, Virginia*). If radon is generated within a dense rock with minimal pore sizes, at most it could migrate only a few centimeters (Tanner 1964). Therefore, in this type of rock, only radon generated within the top few centimeters of the surface could escape and potentially migrate into a building. Conversely, if the rock has a low density and a large pore size and is fractured, the migration of radon can be on the order of hundreds or thousands of feet (Akerblom 1984; Sextro 1987).

Regardless of the primary source of radon (e.g., rock or soil grain), before radon can enter a building, it usually must pass through a layer of soil. The method (e.g., flow or diffusion) and speed of radon movement through soils are controlled by the amount of water present in the pore space (the soil moisture content), the percentage of pore space in the soil (the porosity), and the interconnectedness of the pore spaces, which determines the soil's ability to transmit water and air (Otton et al. 1993). The term "soil permeability" refers to the overall air flow characteristics of a particular soil and is an indicator of the relative ease with which radon moves from its natural matrix into the environment by a diffusion and/or flow mechanism. As with radon transport through rock, extremely dense, nonporous soils (e.g., low-permeability soils, <1.5 cm/h) can significantly reduce the amount of radon available for incorporation into a building. Likewise, if radon is able to move easily in the pore space (e.g., high-permeability soils, >15 cm/h), then it can travel a greater distance before it decays, and it is more likely to collect in high concentrations inside a building (Nagada 1994; Otton et al. 1993).

In summary, the presence of high levels of uranium in the soil and/or rock is not the sole precursor of elevated indoor radon potential. Radon must first emanate from the rock or soil grain and find a pathway through the soil to the building. In dense rock and nonporous compacted soils, the reservoir of radon available for transport into a building can be limited to just the first few inches of rock and/or soil under a building. However, in high-emanation-efficiency rock and/or soil matrixes in contact with a permeable soil, even negligible levels of uranium can produce a high soil gas concentration.

1.2.3 Geological Features that Enhance Radon Transport

In addition, certain geological features, such as karst topography, have demonstrated the capacity for seasonal variation (Gammage et al. 1992). “Karst” is a term used to describe a topography in which surface water or groundwater has dissolved sedimentary rock such as limestone. The result of the erosion is a subterranean network of shafts, tunnels, cavities, and caves (Mammoth Cave in Kentucky is a good example). Also, in most cases, the shafts, tunnels, and cavities connect to the surface (Figure 5). In solid rock, radon can at most diffuse a few centimeters (Tanner 1964). Therefore, for all practical purposes, radon availability is limited to the surface of the rock. However, a karst network greatly increases the surface area of a given formation, resulting in much greater emanation efficiency. The network of caves, tunnels, and shafts then serves to both concentrate the radon and transport it from considerable depths to the surface. Another characteristic of karst networks is that they breathe: whenever the ambient outdoor temperature is different from the ground temperature, the network will exhaust air or draw it in. The driving force is simply that warm air rises and cool air sinks. In flat karst areas, winter levels of indoor radon average 2–3 times those observed in the summer months. In cases in which a karst network is inside a hill, ridge, or mountain, the effect is even more enhanced by the stack or chimney effect. For example, a building built on the top of a hill connected to a karst network will see an order-of-magnitude increase in indoor radon concentration in the winter. Those located at the bottom of the hill will have a similar order-of-magnitude increase, but only in the summer months. Other geological types with similar features include lava tubes, layered basalts and volcanic tuff, weathered granite, and coquina.

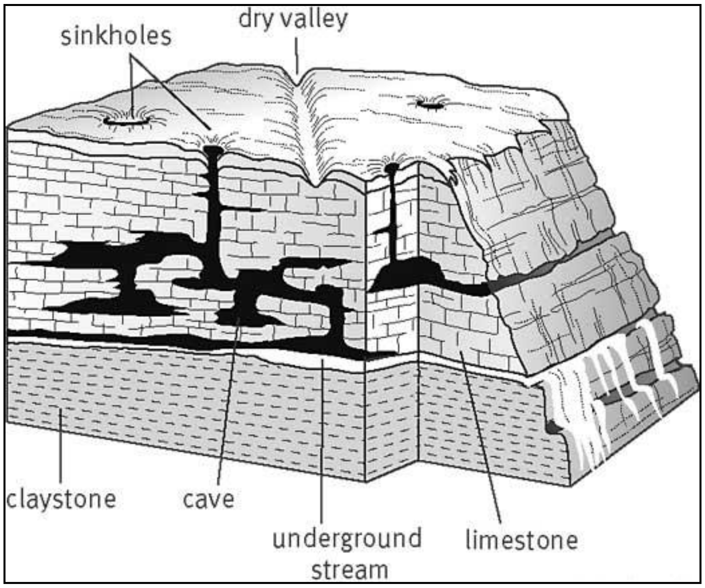


Figure 5. Typical features found in karst topography.

Another example of a geological feature that causes seasonal variation and higher than expected indoor radon levels is sheared fault zones (common in the Appalachian region of the eastern United States). Like karst, these faults result in higher radon emanation from the uranium-bearing formation (rocks with cracks have more surface area than solid rocks) and allow the radon to migrate from considerable depths (upward of 1,000 ft.) and distances (several miles).

In soils, certain types of glacial deposits also enhance the indoor radon concentrations. Many areas of the United States underlain by soils derived from continental glacial deposits generate elevated indoor radon levels (>4 pCi/L). For example, Iowa (71%), North Dakota (63%), and Minnesota (46%) have some of the highest percentages of homes with elevated indoor radon levels in the State/EPA Residential Radon Survey. Determining the radon potential of glaciated areas is complicated by several problems:

1. Surface radioactivity is generally uncharacteristically low in glaciated areas and does not appear to correlate well with indoor radon values.
2. Because glaciers redistribute the bedrock they override and entrain, the composition and physical properties of till soils do not necessarily reflect those of the underlying bedrock (transport distances were much further for the continental glaciers of the Great Plains and Great Lakes regions than for glaciers in New England or for valley glaciers.
3. Where glacial cover is thin, the radon potential may be a complex product of the glacial cover and the underlying bedrock. Crushing and grinding of rocks by glaciers increases the mobility of uranium and radium in the resulting tills, allowing them to move readily downward through the soil profile with other mobile ions as the soil is leached.

> Because of these day-to-day and seasonal variations, the Committee on Biological Effects of Ionizing Radiation (BEIR) VI (BEIR VI 1998) conceded that although all exposure to radon increases the risk of contracting lung cancer, the need for corrective action should be based on an integrated 1-year average, not on short-term excursions.

1.3 HOW RADON ENTERS A BUILDING

Radon, a gas at ambient temperatures and pressures, migrates from the surrounding soil into buildings through cracks in concrete slabs and basement foundation blocks, through pores in concrete masonry units, and through air spaces around pipes (ASHRAE 2010, *Indoor Air Quality Guide*). It can also collect in crawlspaces and then flow into living and work areas. The flow of radon into the living area of a building is caused by both natural diffusion and pressure-assisted flow. However, natural diffusion usually contributes only a small amount of radon within a building; in most cases, radon above ambient levels can be attributed to pressure-assisted flow.

The process of pressure-assisted flow can be either natural or man-made. The rising and exiting of warm air within a building causes natural pressure-assisted flow, or thermal stack effect. As warm air rises, makeup air is pulled into the building through slab and wall imperfections. If the imperfections are in contact with soil, the building radon concentration increases. Man-made enhancement of radon entry is primarily the result of negative pressure created by the operation of a furnace, air-conditioning system, ventilation fan, or air exhaust system.

The physics of radon transport and retention in a building are very complex. The radon source term is the total quantity of radon entering the structure per unit of time (pCi/h). Studies by EPA and the US Department of Energy (DOE) have identified more than ten variables that contribute to the source term (e.g., radium content of the soil, emanation efficiency of the soil matrix, soil permeability, soil water content, various temperatures, and shell and subslab pressures). After radon has entered a structure, many other variables either enhance or dilute it. The term relative air change refers to the rate at which outdoor air infiltrates into the building shell and inside air is exhausted (for both natural and man-made causes). Generally speaking, if the radon source term is greater than the relative air change, then elevated radon levels will result. Because of these variables, there is no certain way to predict the radon level of a particular building. The only sure way to know if a room/building has elevated indoor radon levels is to test.

1.3.1 Indoor Radon Retention

Although radon diffusing through and, in rare cases, from concrete (e.g., wall, floors, piers, beams) can contribute to the indoor radon level, the main driving force for most buildings is the pressure differential caused by the stack effect (the rising and escape of warm air in a building through the upper floors) and the negative pressures caused by the operation of mechanical exhaust systems within a building (e.g., bathroom exhausts, fume hoods, combustion appliances and furnaces). In addition, episodic weather conditions, such as wind and rain, can induce a pressure differential that results in transient increases in the building radon level.

Although the physics of radon transport into and retention in a building are complex (more than ten variables have been identified to date), it can be approximated as a simple dilution ventilation problem using a source term (pCi/h) into a fixed volume (ft^2), with a known ventilation rate (h^{-1}). Because the volume of a structure is fixed, the equation can be further simplified to demonstrate that elevated radon levels in a building is strongly linked to the overall ventilation rate of the building, meaning that buildings with high ventilation rates have lower elevated radon potential. Conversely, buildings with lower ventilation rates have higher elevated radon potential. However, the relationship between ventilation rate and radon concentration is not 1 to 1; at a constant source term, halving the ventilation rate doubles the radon concentration (EPA 1988a, *Radon Reduction Techniques for Detached Housing*, EPA 1988a, 625/5-87/017). This variable, air-change per hour (ACH), is a function of how tightly the building was constructed and is regulated by the requirements of local building and energy codes. Nationally, the ACH ranges for residential and nonresidential construction are from 0.25 h^{-1} in colder (e.g., Minnesota) or hot and humid (e.g., Florida) climates to over 1.5 h^{-1} in the temperate tropical areas (e.g., Hawaii). The significance of the relationship between indoor radon levels and a building's ACH is as follows. Assume for a source term that you have 500 pCi/L of soil gas (average for most parts of the United States) under a slab that results in a 2 pCi/L radon level (the approximate indoor national average) for a house with an ACH of 1 h^{-1} (typical for homes built in Hawaii). The same home in Tennessee, under identical conditions but with a typical ACH of 0.5 h^{-1}, would have a radon level of 4 pCi/L. But, if the home was in the upper Midwest, with a typical ACH of 0.25 h^{-1}, the home would have 8 pCi/L. Therefore, when considering elevated indoor radon potential, in addition to the geological variables found in soil and rock, local building practices must be considered.

As can be seen in Figure 6, a rain event that lasted only a few hours resulted in an order-of-magnitude increase in the radon concentration. The time required for the dissipation of such a radon spike depends mostly upon the ventilation rate of the building. For example, if the building has an air change rate of 0.5 h^{-1}, the spike would usually dissipate within 6 h (assume in this example that three air volumes are required to remove a gas pollutant). However, in some cases (e.g., buildings with tight envelopes or buildings with fresh-air makeup greatly reduced), the radon spike may require days or even weeks to fully dissipate. As a result, the integrated concentration in the room over time would vary significantly depending upon the frequency (how often) and quantity (how much) of rainfall within a certain time period. Additional information on CRMs measurements has been included in Sections 3.4.1 and 5.1.9.

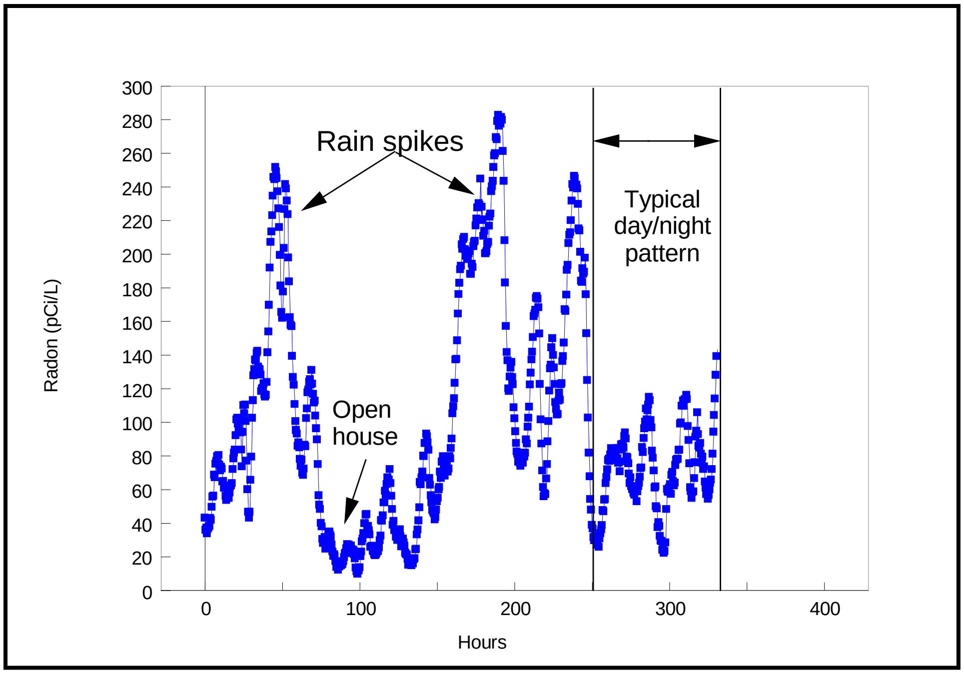


Figure 6. Example of short-duration events on radon concentration.

1.3.2 Episodic Events that Impact Indoor Radon Levels

Unlike other common indoor environmental concerns (e.g., lead-based paint and asbestos), indoor radon concentration can vary significantly from day to day and from season to season. The day-to-day variation in radon concentration is usually caused by episodic weather events such as rain and wind but can also be caused by actions of the building occupants (e.g., leaving doors or windows open; see Figure 6). For these reasons, EPA recommends that all short-term testing (testing for <90 days) be performed during normal weather patterns and under closed building conditions (e.g., windows and doors are closed except for routine entrances and exits). With respect to seasonal variation (e.g., heating vs. cooling season), the range observed is dependent upon the geographical region and climate. For example, in the northeastern United States, radon concentrations are typically 50% higher than normal in the winter, vs. 25% higher in the Southeast. Other studies (Lin et al. 1999) have found that a single short-term measurement is typically within a factor of 1.8 of the long-term measurement. Opinions vary as to why this is observed (e.g., increased stack effect in the winter, prolonged periods of closed building conditions, ground freeze, and snow cover), but most experts agree it results from a combination of many things and not just a single cause.

1.3.3 Distribution of Radon within Nonresidential Buildings

Residential studies by DOE and EPA have shown that on the same floor level, the radon concentration does not vary significantly from room to room in most single-family homes.

It is for these reasons that, other than recommending that the test be performed on the lowest occupied level, EPA protocols do not specify which rooms to test (EPA May 1993, 402-R-92-003). However, unlike in residential buildings, the distribution of radon within nonresidential buildings does vary significantly from room to room. In fact, studies by DOE have found that for buildings >2000 ft^2 with elevated radon levels, over 95% of the time, only one in four rooms tested positive (Wilson et al. 1991b). With respect to using statistical means to estimate the extent of elevated radon potential in large buildings, statistical analysis of large nonresidential data sets (Wilson et al. 1991b.) has found that over 70% of the time, the elevated result(s) would not have been predicted at a 95% confidence level. Further modeling of the radon data, the objective of which was to predict the presence of one room with elevated radon levels in a building, found with 95% confidence that 95% of the rooms needed to be tested. It is for all these reasons that EPA recommends the testing of all occupied ground-contact rooms in its nonresidential testing protocol (EPA July 1993, 402-R-92-014).

There are many accepted reasons for this disparity in room-to-room concentration. For one, slabs in nonresidential buildings are larger, meaning a greater volume of radon can accumulate in the fill area under the slab. In addition, because of higher load considerations, large buildings typically have more internal footings and expansion joints per unit area of slab than does residential construction. Also, large buildings tend to have more numerous floor penetrations for water, sanitary, electrical, and communications purposes. Another difference is interior design: to prevent the spread of smoke during a fire, floor-to-ceiling fire walls are typically used throughout a large building. This design feature tends to isolate rooms and areas from one another within the building by reducing the natural flow of air from one zone to another. Finally, large buildings have larger mechanical systems, which move significant volumes of air. If these systems are not balanced, certain areas of the building may become depressurized relative to the soil beneath it. If openings are present within the slab in those rooms, the concentration of radon soil gas entering those rooms will increase significantly. In fact, DOE studies have found that in nonresidential buildings with elevated radon levels, only about one-third of the elevated radon concentration is directly attributed to traditional radon entry mechanisms (e.g., diffusion, migration through cracks). An equal amount was attributed to a combination of mechanical and building design features (e.g., the radon gas is actively being mined from the soil), and the remainder is a combination of both mechanisms.

In summary, the distribution of room-to-room radon concentrations in large buildings is different from the distribution in residential buildings simply because the buildings are designed and conditioned differently. For that reason, all occupied, ground-contact rooms need to be tested to determine if the occupant is at risk.

1.3.4 Distribution of Radon within a Family Housing Population

In most cases, radon levels within a large population of family housing follow a log-normal distribution. For this reason, various screening approaches can be applied to a population of family housing to estimate the population radon potential for planning purposes. From a quality data set, statistical projections can be performed as to the likelihood and projected number of units that may be present in a given population with radon levels ≥ 4 pCi/L. This approach is suitable for triaging different populations of family housing for future assessment and for making projections for the number of units that may have elevated radon levels. The difficulty in implementing this approach is that you must have a representative sampling or all housing types in the population along with a good geographical distribution. In addition, enhanced quality control is required to provide the smallest measurement uncertainty that the measurement device can provide. Because of this, in the late 1980s Navy Family Housing performed a statistical study to determine the best trip-wire sampling approach with a 95% confidence that no more than 1 untested unit in a population would be ≥ 4 pCi/L. In this approach a fixed percentage of units are tested (most common is 10 or 25%) and full assessment is only performed if one or more units are found to be ≥ 4 pCi/L. Monte Carlo simulations determined that the 95% confidence interval in a trip wire approach could only be achieved with 25% sampling if 10 out of 100 units in the sampled population had elevated radon. At lesser numbers of elevated units, the statistical confidence dropped to unacceptable levels (Table 1). In 2002, using tens of thousands of naval family housing data these Monte Carlo findings were confirmed. For this reason, NAVRAMP, EPA and the radon industry standards recommend that all ground contact housing be tested for radon at an installation.

Table 1. Monte Carlo successful simulations as a function of sample size in family housing.

Units > 4 pCi/L	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
10% sampled	10%	19%	27%	35%	41%	47%	53%	58%	62%	66%
25% sampled	25%	44%	58%	69%	76%	82%	87%	90%	93%	95%
33.3% sampled	34%	56%	71%	81%	87%	92%	94%	96%	98%	99%
50% sampled	50%	75%	88%	94%	96%	99%	99%	100%	100%	100%
66.6% sampled	67%	89%	96%	99%	100%	100%	100%	100%	100%	100%
75% sampled	75%	93%	99%	100%	100%	100%	100%	100%	100%	100%
80% sampled	80%	96%	99%	100%	100%	100%	100%	100%	100%	100%
90% sampled	90%	99%	100%	100%	100%	100%	100%	100%	100%	100%
95% sampled	95%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Another issue is the sampling interval within multi-family housing (duplex, townhouse, and apartment building). At the time that the NAVRAMP was developed in 1988 some testing protocols only required the testing on one unit per multi-family building. The key assumption being that radon levels within a multi-family were consistent in all units within the building. A review of the available data by DOE and the Navy identified specific examples in which this was not true. As a result, the NAVRAMP protocol was changed to test all ground contact units within a multi-family housing building. In 2002, a review of tens-of-thousands multi-family measurements collected within the Navy and USMC, confirmed that testing all units within a multi-family housing building was required (Section 3.3.1). Another finding was that the number of units within a multi-family housing building (e.g., duplex vs. 8-plex) made no difference in the probability of having elevated radon levels. For this reason, NAVRAMP, EPA and the radon industry standards recommend that all ground contact housing in multi-family buildings be tested for radon at an installation.

1.3.5 Surface Radon Potential and Indoor Radon Levels

In the late 1980s and 1990s, USGS, EPA, and DOE expended considerable effort in attempting to correlate radon soil gas concentrations and indoor radon levels (Tanner 1986 and 1992). The primary hypothesis of these studies was that if the radon flux at the surface could be measured accurately, the number of homes in a given area with elevated radon potential could be estimated. If true, this correlation would assist state and local governments in coordinating their respective radon programs and determining if radon-resistant features in new construction were needed. Unfortunately, during these studies, many variables at the surface/building interface were identified which proved difficult to estimate in advance (e.g., estimating the total leakage surface area of the slab for all cracks, joints, and plumbing fixture openings). In addition, order-of-magnitude changes in the radon soil gas concentration were observed at some of the sites because of variations in microgeology. Estimating a building's shell natural ventilation rate and the stack effect of the structure proved difficult as well. In light of all these uncertainties, EPA concluded that radon surface flux or soil gas measurements at a given location did not provide sufficient assurance whether indoor elevated radon levels would be present. In addition, the costs of such measurements were orders of magnitude higher than simply incorporating radon-resistant features into new construction and testing afterward.

1.3.6 Radon from Building Materials

The precursors for radon—uranium, radium, and thorium—are found naturally in all geological formations. Therefore, in any building where concrete (processed limestone) or decorative stone (e.g., marble, granite, shale) is present, radon is being emitted. In the case of concrete, in the 1970s, homes located in Durango and Grand Junction, Colorado, were found to contain high levels of radon in addition to high radiation levels. The source of the radon and radiation was later determined to be processed uranium mill tail sand that had been used as aggregate in the concrete and cement block in the homes. In response to the health hazards posed by this exposure, Congress enacted the Uranium Mill Tailings Radiation Control Act of 1978. This Act established two programs to protect the public and the environment from uranium mill tailings and prohibited the use of uranium mill tailing sands in building construction. In the 1980s similar problems with radon and elevated radiation were also found in the southeastern United States, where processed phosphate slag had also been used as an aggregate within concrete and cement block manufacturing. A series of environmental regulations were then enacted which prohibited the use of these materials in building construction as well.

For concrete that came from gypsum, fly ash, and limestone, studies by EPA in the late 1980s found minimal contribution to the indoor radon level. With respect to decorative stone, a series of news articles in 2008 indicated that high levels of indoor radon were linked to granite countertops. Studies by the decorative stone and radon industry and by EPA concluded that this claim was false for almost all granites on the commercial market.

More recently, the issue of elevated indoor radon linked to building materials has emerged within buildings that have had significant weatherization upgrades or in new construction with high energy-efficiency ratings. The common denominator in all cases observed thus far has been extremely low ventilation rates ($<0.1\ h^{-1}$) within buildings made of concrete (floor, walls, and ceilings). Although the emanation rate of radon from the concrete was found to be low (buildings at the same site made from the same concrete but without weatherization upgrades tested extremely low for radon), the low ventilation rate allowed the radon to concentrate (empirically speaking, if you halve the air change rate, you double the radon concentration). These findings, although rare (>99% of all elevated indoor radon is directly linked to radon soil gas), are predicted to become more common in the future as building codes require tighter buildings to address climate change concerns.

Another example of elevated radon levels from nontraditional sources is cases in which radon is emanating from materials stored within the building. For example, a storage facility containing approximately 1,000 tons of river sand (radon activity 0.07 pCi/g) gave rise to 8.5 pCi/L within the occupied areas of the building. Another facility that warehoused thorium lantern mantels was found to have elevated radon levels as well. Although these cases were extremely rare, the cause—substandard ventilation—was the same.

1.3.7 Radon from Groundwater Sources

The ^{222}Rn concentration in groundwater is due to the decay of ^{226}Ra contained within the rock and soil surrounding the aquifer. As radon gas is generated, it diffuses through the soil and rock and then percolates through the water. Because radon is soluble in water (230 cm^3/kg at 20°C), it can concentrate to levels much higher than that of the dissolved ^{226}Ra. Release of the radon into the indoor environment occurs at point sources wherever the water is used (showers, sinks, clothes washers) and from hot water heaters. According to EPA, approximately 10,000 pCi/L of radon in water is needed to increase the indoor radon level by 1 pCi/L. Because the average waterborne radon level in public groundwater supplies is 353 pCi/L (EPA 1985, 520/5-85-008), radon in water is not considered a major contributor to airborne radon exposure. However, according to the Centers for Disease Control (CDC), 30 to 1,800 deaths per year are attributed to the ingestion of radon in water. Because of these health concerns, Congress included radon in the 1996 Amendments to the Safe Water Drinking Water Act. To address this concern, EPA made available a multimedia mitigation program to address radon risks in indoor air and from drinking water. This option affords states the opportunity to develop enhanced state programs to address the health risks from radon in indoor air, while individual water systems reduce radon levels in drinking water to 4,000 pCi/L or lower. Currently, EPA is encouraging states and sister agencies to adopt this option because it is the most cost-effective way to achieve the greatest radon risk reduction.

1.4 RADON EXPOSURE RISKS

For many years, radon was not considered a health problem in residential buildings; however, in 1984, private homes in the Reading Prong area of Pennsylvania were discovered to have levels of radon in excess of federally mandated exposure limits for radiation workers. Nero et al. (1986) estimated that about one million American homes have radon levels in excess of 8 pCi/L. In 1988, studies by the National Research Council and BEIR found that excessive exposure to radon progeny resulted in a higher-than-predicted number of deaths from lung cancer in mining populations (BEIR VI 1988). Based on this and other information, the EPA estimated that from 5,000 to 20,000 lung cancer deaths per year are attributable to radon exposure (EPA 1986, *A Citizen's Guide To Radon*, OPA-86-004). In 1996 the World Health Organization (WHO) acknowledged that worldwide, radon exposure was the second leading cause of lung cancer, behind smoking (WHO April 1993). More recently, BEIR VI (1999) reinvestigated the health risks associated with radon exposure. Using information from previous studies and supplementing it with information from more recent laboratory studies, the committee estimated that approximately 11,000 lung cancer deaths per year were attributable to exposure to radon (BEIR VI 1998). These mortality estimates make exposure to radon the second-leading cause of lung cancer, behind smoking. Statistically speaking, an individual's lifetime risk of dying from radon lies between the risks of being killed by a drunk driver and drowning (Figure 7). Individual relative risk from radon exposure is summarized in Table 2. These findings were borne out by other studies noted by WHO in 2009 (WHO 2009). However, corrective actions (i.e., mitigation, see Chapter 4) greatly reduce these lifetime lung cancer risks (EPA May 2012, EPA 402/K-12/002).

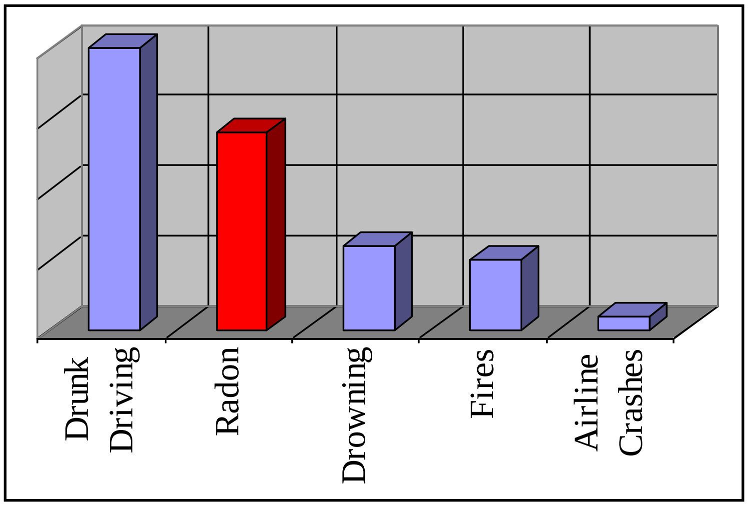


Figure 7. Lifetime relative risks to radon exposure.

1.4.1 Impact of Radon Exposure on Lung Tissue

The subsequent radioactive decay products of ^{222}Rn, more commonly referred to as radon progeny, consist of four short-lived radon progenies (polonium-218 [^{218}Po], lead-214 [^{214}Pb], bismuth-214 [^{214}Bi], and polonium-214 [^{214}Po]) (Figure 2)] and three long-lived radon progenies (lead-210 [^{210}Pb], bismuth-210 [^{210}Bi], and polonium-210 [^{210}Po]). Of these seven, typically only the short-lived progeny is considered a health risk. Unlike radon, which is chemically inert, radon progeny are chemically reactive metals that can attach to walls, floors, and airborne particles or combine with water vapor and other gases in the air. The portion of the radon progeny attached to particles in the ambient atmosphere is called the "attached fraction," whereas "unattached fraction" refers to suspended individual atoms or ultrafine particle clusters. Radon progenies that attach to walls or other surfaces are considered to be "plated out" and therefore removed from the air, so they can no longer be inhaled. When the short-lived radon progeny (attached or unattached) is inhaled, a portion of them can attach to the lining on the bronchioles of the lungs. Because of their short half-lives, the lung cannot clear itself of these materials before they undergo radioactive decay. Of particular importance are ^{218}Po and ^{214}Po, which emit highly energetic alpha particles. These alpha particles can strike sensitive cells in the bronchial tissue and cause damage that could lead to lung cancer. It is these two polonium radionuclides that produce the bulk of the radiation dose to the lung and create the greatest source of risk of lung cancer from exposure to radon and radon progeny (EPA May 1992, 400-R-92-011; EPA 1993a, 402-K-93-008).

Table 2. Lifetime radon exposure risk

Radon level (pCi/L)	Number of lung cancer deaths per year per 1000 people	Comparable risks
200	440–770	More than 60 times the lung cancer risks of nonsmokers
		Four packs/day smoker
100	270–630	
		20,000 chest x-rays per year
40	120–380	
		Two pack/day smoker
20	60–120	
		One pack/day smoker
10	30–120	
		Five times non-smoker risks
4	13–50	
		200 chest x-rays per year
2	7–30	
		Nonsmoker risk of lung cancer
1	3–13	
0.2	1–3	20 chest x-rays per year

Source: EPA, *A Citizen's Guide to Radon,* OPA-86-004, 1986.

1.4.2 Radon-Related Lung Cancer Vs. Other Types of Cancer

Compared with other types of cancer, the National Cancer Institute's 2010 Surveillance, Epidemiology, and End Results study identified deaths from lung cancer due to radon as number 3, just behind deaths from leukemia and lymphoma (Figure 8.). A copy of the study is available at http://seer.cancer.gov/csr/1975_2007/results_single/sect_01_table.01.pdf . Additional information can be obtained at http://www.cancer.gov/.

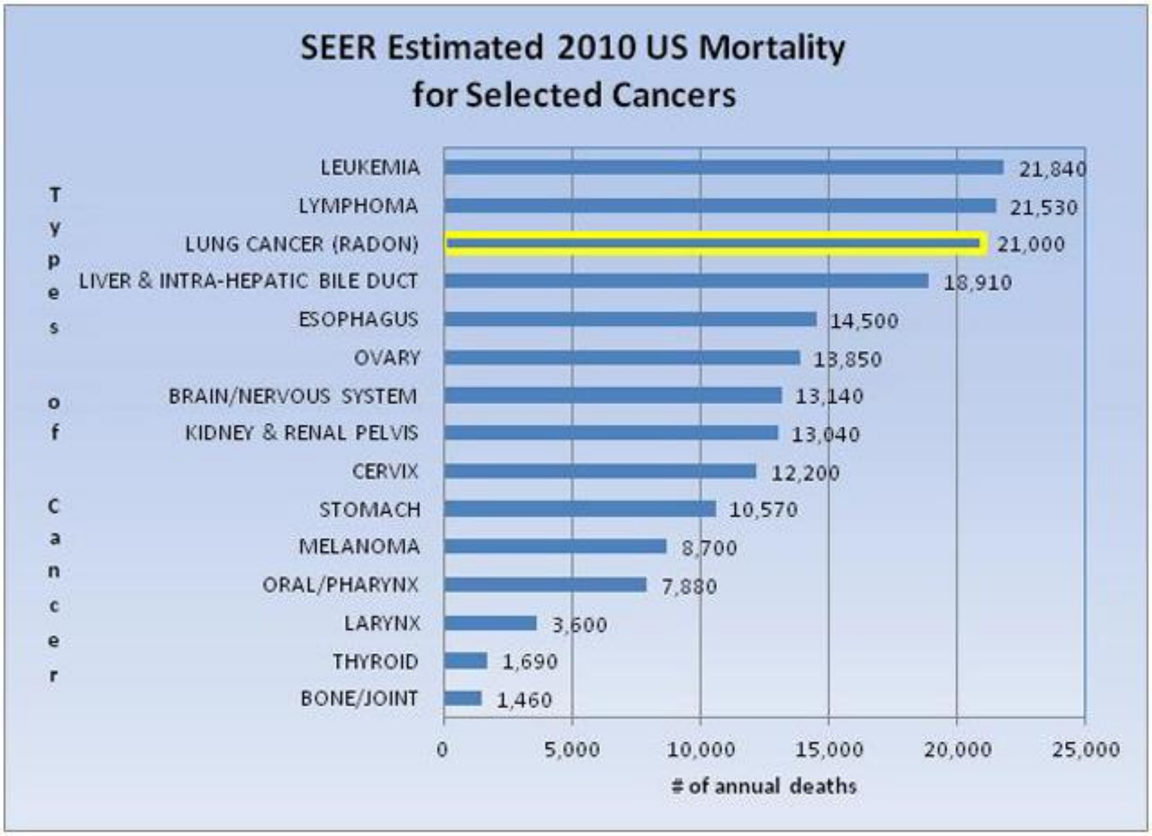


Figure 8. Surveillance, Epidemiology, and End Results (SEER) 2010 findings.

1.5 EPA CORRECTIVE ACTION GUIDELINES

In 1986 EPA published the first of five subsequent editions of *A Citizen's Guide to Radon* (EPA 1986, 1994, 2007, 2009, 2012). Unlike other EPA publications, the follow-up editions did not supersede or replace previous editions; they only provided additional information and, in the case of subsequent editions (the most recent is EPA May 2012, 402-K-12-002), a more user-friendly format. The key points in these documents are as follows:

1. There are no safe levels of radon. Exposure to the average outdoor level found in the United States is roughly equivalent to 20 chest x-rays per year.
2. Because of the cost of reducing the radon levels in homes, EPA established a guideline of 4 pCi/L as an action level based on reducing the radon risk to the general population at a reasonable cost.
3. In the subsequent editions, the significantly increased risks of radon exposure and smoking were also included.

In the 1986 edition of *A Citizen's Guide to Radon*, EPA provided a recommended timeline for corrective action (Table 3). This timeline, although excluded from later editions, is still a useful guide in determining when to take corrective action. However, EPA currently recommends that corrective action be taken as soon as possible (EPA May 2012, 402-K-12-002).

Table 3. *A Citizen's Guide to Radon* corrective action schedule

EPA radon action levels (pCi/L)	Recommended actions
0 to <4	No action required
4 to <20	Mitigate within a few years
20 to <200	Mitigate within a few months
≥200	Mitigate within several weeks

Source: US Environmental Protection Agency, *A Citizen's Guide To Radon,* OPA-86-004, 1986.

In comparison, the WHO (WHO 2009) has recommended that the action level for industrialized countries be set at 100 Becquerel per cubic meters (Bq/m^3, 1 pCi/L= 37 Bq/m^3) or 2.7 pCi/L. Note that Bq/m^3 is the international unit of radon measure.

1.6 OCCUPATIONAL SAFETY AND HEALTH ADMINISTRATION AND RADON

In 1988 a memorandum of understanding between Occupational Safety and Health Administration (OSHA) and the Nuclear Regulatory Commission (NRC) was generated to outline areas of worker protection responsibility between the two agencies within NRC licensed facilities. The memorandum clearly stated that NRC was responsible for radiation worker protections for occupational exposure from licensed radioactive material (e.g., nuclear powerplant workers) and machine produced radiation such as x rays (e.g., medical workers). The memorandum also excluded other types of workers which were covered by other regulatory bodies (e.g., miners, truck drivers, railroad workers and state and local public workers). However, OSHA accepted responsibility for worker protection from natural background radiation for federal (with the traditionally noted exceptions with DoD and DOE) and applicable private workforce. In 1989, OSHA acknowledged that radon in the workplace within a structure controlled by the employer would fall under CFR 29 1910.1096. In 1994, in a letter to the US Navy, OSHA defined a radiation area as any location which has an exposure which exceeds 7.5 pCi/L for a 40 h work week (Anku, 1994, Appendix B). Therefore, all requirements in 29 CFR 1910.96 and 29 CFR 1926.53 would apply. In summary, naturally occurring radon in the workplace would apply wherever OSHA had jurisdiction.

The current OSHA Ionizing Radiation standard [29 CFR 1910.1096 (OSHA 1996)], is based upon Atomic Energy Commissions (AEC) 10 CFR 20 regulations from 1969. Unfortunately, the current OSHA standard does not refer to this fact nor does it make it clear to consult more recent radiation regulations from the NRC (the successor to AEC). This in turn leads to a common misconception that OSHA does not require radon monitoring or mitigation for any workspace that is < 100 pCi/L. However, if the more current radiation standards are applied (2014 NRC) the monitor threshold would be set at 3 pCi/L.

It is important to note that 29 CFR 1910.1096 is not a corrective action standard, it is a standard specifically designed for the monitoring of individual dose within the workplace with specific limits for quarterly exposure to radon. Under the standard, the workplace is divided into two areas: restricted where radon levels are > 3 pCi/L and unrestricted areas where radon levels are < 3 pCi/L, with each area having to have its own requirements for posted warning signage, personnel monitoring and dose records retention. In 2016, Lewis (Lewis, 2016) stated that 29 CFR 1910.1096 also required:

- Personnel monitoring would be required if 25% of the dose limits may be exceeded in any calendar quarter [1910.1096 (d)(2)(i)];
- If personnel monitoring is required, then radiation exposures records must be maintained [(1910.1096 (d)(2)]; and
- Restricted access to the public would be required [1910.1096 (a)(3)].

In 2015, OSHA informed the Navy that if 29 CFR 1910.1096 was implemented within a building, that all requirements of the regulation had to be performed for both restricted and unrestricted areas in the building. In other words, posted warning signage, personnel monitoring and dose records retention would be mandatory. However, if the building were mitigated in accordance with EPA guidelines (OSHA 2011, 3430-04-2011) implementation of 29 CFR 1910.1096 would not be required.

2. OVERVIEW OF THE NAVRAMP

2.1 US NAVY RADON POLICY

The current Navy Radon Policy established in Chapter 25, Section 3.2 of OPNAV M-5090.1 (US Navy 2021) provides the framework for the implementation of the radon program within the Navy. Briefly, it does the following:

1. Instructs all Navy installations to implement NAVRAMP worldwide.
2. Establishes 4 pCi/L as the action level for both residential and occupational radon exposures.
3. Limit's radon testing to occupied buildings.
4. Requires periodic inspections and preventive maintenance as appropriate on mitigation systems and periodic retesting of rooms or buildings with mitigation systems to ensure the systems are operating properly to reduce building radon levels below 4 pCi/L. In addition, retesting within these buildings is required, if the structures have been significantly modified, to ensure levels are still below 4 pCi/L.
5. Requires, where applicable, that radon-resistant features be incorporated into new building construction.
6. Requires installations to evaluate all existing and new lease agreements to ensure that Navy occupants are afforded the same protection from elevated levels of radon as those that are in Navy-owned buildings.
7. Requires US Navy Bureau of Medicine and Surgery (BUMED) to assist COMNAVFACENGCOM in areas of radon public health assessment and risk communication and evaluate the appropriateness of radon action levels and mitigation schedules for Navy installations.

Chapter 25, Section 3.2 of OPNAV M-5090.1 (US Navy 2021) divides radon testing into three phases:

1. **Screening.** Installations must select a statistically significant sample of structures (minimum 95 percent confidence that no more than one room has the potential for elevated radon), mainly family housing. Included in the selection of buildings will be all hospitals, bachelor quarters, schools, childcare centers, and brigs. A "screening" becomes an "assessment" if the minimum statistically significant number of buildings (31 buildings per installation or 31 housing units per housing area) is equal to or greater than the total number of occupied buildings. Radon testing within these selected structures must be conducted using the appropriate EPA testing protocols as described in *Navy Radon Assessment and Mitigation Program Guidebook for Naval Shore Installation.* Under normal circumstances,

screening is performed only once, and therefore should not be considered a recurring requirement.

2. **Assessment.** If, during the screening process, an installation detects elevated radon levels and confirms the level is equal to or greater than the 4 pCi/L action level, then the installation must test all ground-contact family housing units and all occupied and occupiable testable buildings at the installation for radon using the appropriate testing protocol as described in the NAVRAMP implementation guidance, *Navy Radon Assessment and Mitigation Program Guidebook for Naval Shore Installation.* This requirement applies even to buildings where initial screening showed the radon level was below the EPA-recommended action level.

3. **Monitoring.** After screening or assessment has been completed, all installations must implement monitoring. At installations where elevated radon levels have been detected, radon testing must be performed every 5 years for all buildings, including those where mitigation systems have been installed. At installations where no elevated radon levels were found during screening, testing must be performed in all new construction and acquisitions, within all occupied and occupiable testable buildings constructed after 2003, and in all priority structures (e.g., hospitals, bachelor quarters, schools, childcare centers, brigs) if they were not tested previously.

With respect to mitigation, OPNAV M-5090.1 (US Navy 2021) states that “Activities must install and maintain a mitigation system in buildings determined to have indoor radon levels with validated monitoring results above the EPA-recommended action level of 4 pCi/L to reduce radon levels below 4 pCi/L and must schedule mitigation steps conforming” to the priority scheme in Table 4.

Table 4. Corrective action timeline. [a, b]

Radon level (pCi/L)	Action
0 to <4	No action required
4 to <20	Mitigation within 2 years
20 to <200	Mitigation within 6 months
≥200	Mitigation within 3 weeks

[a] The schedule for corrective action (e.g., the mitigation clock) should be based upon the testing report date. In cases where confirmation is required, mitigation should be based upon the testing report date of the initial test.

[b] Corrective action schedule is based on recommendations made by the US Navy Bureau of Medicine and Surgery (February 2000).

For installations in which elevated radon potential is known or suspected, OPNAV M-5091.1 (US Navy 2021) states that “Installations must incorporate appropriate radon-resistant new construction (RRNC) techniques into the design and construction phases of new buildings or significant modifications to existing buildings (where necessary due to applicable regulatory requirements, historical data, and geological conditions at the location) to prevent indoor radon levels from exceeding the EPA-recommended action level of 4 pCi/L."

Overseas Navy and Marine Corps installations may be required to meet the country-specific Environmental Governing Standards prepared by the Department of Defense (DoD) Environmental Executive Agent based on the host nation's environmental requirements and the Overseas Environmental Baseline Guidance Document.

Naval Facilities Engineering and Expeditionary Warfare Center (NAVFAC EXWC) maintains a central radon data management system containing results for radon testing conducted per NAVRAMP implementation guidance (this document). Installations are responsible and shall maintain records of all NAVRAMP testing data and mitigation projects and shall provide testing data to NAVFAC EXWC within 90 days of the acceptance of the radon testing report (Guidebook Section 3.5).

2.2 US MARINE CORPS RADON POLICY

Marine Corps policy is established under Volume 6, Chapter 3 of US Marine Corps MCO 5090.2, Environmental Compliance and Protection Manual (US Marine Corps 2018). Briefly, the policy states that all Marine Corps installations must implement all phases of NAVRAMP and incorporate radon-resistant designs in new construction where required by site data showing historical levels of elevated radon, geological conditions, or regulatory requirements. Installations are responsible and shall maintain records of all NAVRAMP testing data and mitigation projects and shall provide testing data to HQMC/MCICOM GF-Environmental. Data submission guidance is to be provided upon request.

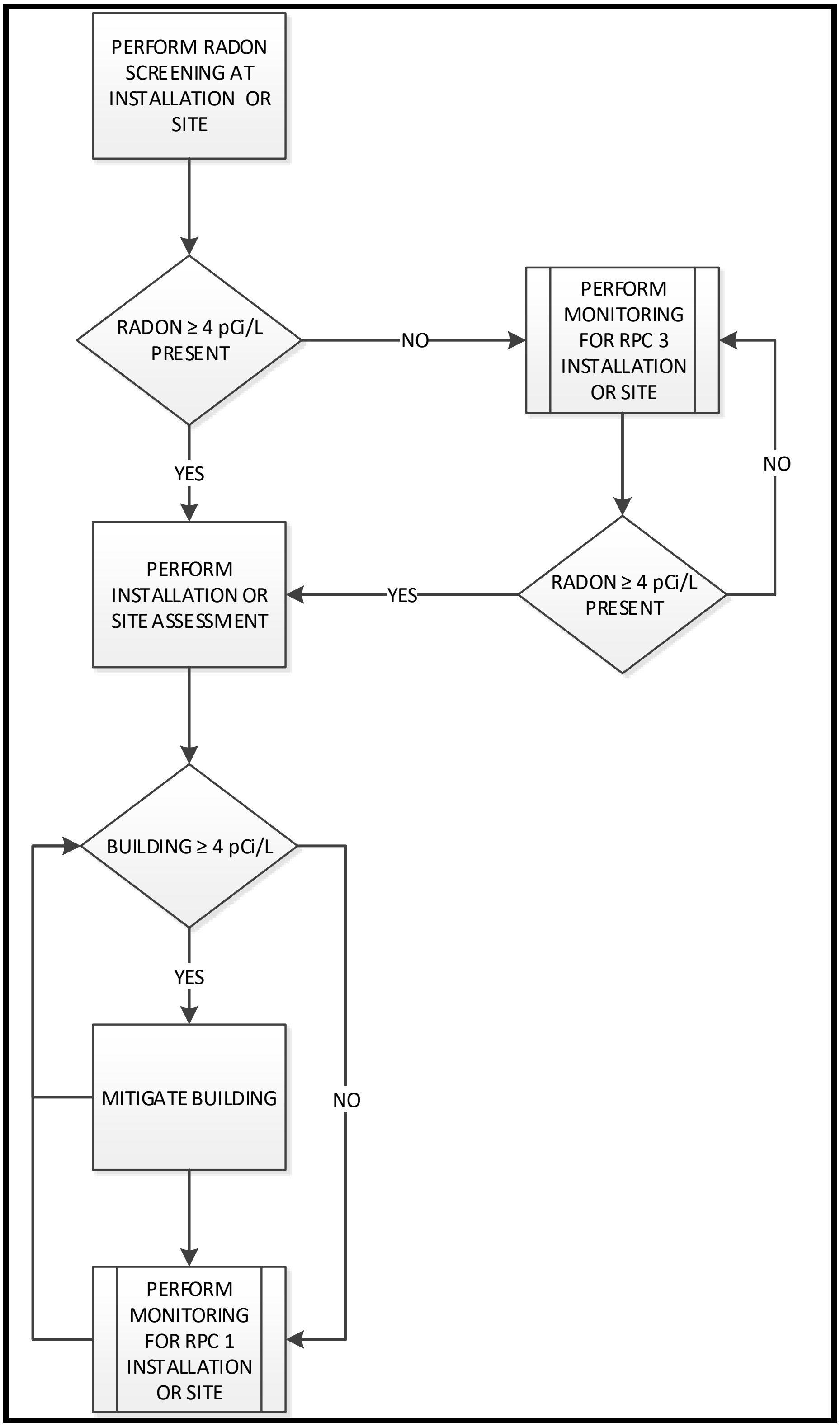
2.3 SYNOPSIS OF THE NAVRAMP

The NAVRAMP is an ongoing, multiphase program designed to ensure that Navy and USMC military staff, civilian employees, and dependents who are occupying testable Navy or Marine Corps buildings are continuously protected from exposure to elevated radon levels (Flowchart 1). Based upon historical radon test results, installations are placed into one of three NAVRAMP Radon Potential Categories (RPC, NAVRAMP Guidebook Section 2.4), which define the actions the installation must take. Briefly the RPCs are:

RPC 1: Installations or sites with known elevated radon potential (e.g., elevated radon levels have been confirmed within buildings at the installation)
RPC 2: Installations or sites with unknown radon potential
RPC 3: Installations or sites with sufficient radon testing data that indicate low radon potential

After initial screening has been completed, all installations are transitioned into RPC 1 or RPC 3 monitoring categories, with each category having its own distinct requirements (NAVRAMP Guidebook Section 2.7).

Under OPNAV M-5090.1 (US Navy 2021) and NAVRAMP, all occupied rooms and housing units with confirmed radon levels ≥ 4 pCi/L must be mitigated. The timeline for corrective action begins with the testing report date (NAVRAMP Guidebook Section 3.5). The time for corrective action is based upon the radon levels with the higher elevated radon levels having the least time for corrective action (Table 4). If elevated radon potential is known or suspected at an installation, basic logistical mitigation planning should be performed before or during the sampling period. This should include not only identifying possible funding sources and contractual mechanisms for radon mitigation services but also determining if accredited radon mitigation contractors are available in the area.



Flowchart 1. Overview of the NAVRAMP testing and mitigation phases.

2.4 EPA CORRESPONDENCES WITH THE NAVY

Since the radon programs inception, the US Navy has maintained a positive working relationship with the EPA. These interactions have kept the NAVRAMP on the forefront of radon testing and mitigation. For example, in 1990, EPA was able to corroborate the findings of the DOE/Navy study for the need to test all ground contact rooms in a nonresidential building. Previously testing every 2,000 ft2 was the accepted sample density. Along similar lines, EPA in 1991 was able to also confirm in multi-family housing the DOE/Navy findings that all units in ground contact needed testing. Previously it had been 1 per building.

In 2011, EPA (Appendix A) provided the Navy with clarifications of past EPA protocols and guidelines and made some new recommendations with respect to the management of radon. Recognizing that elevated radon levels are a highly localized phenomenon, meaning that radon concentrations can vary significantly from building to building, EPA's overall position is biased toward testing every building at all naval installations (i.e., screening is no longer a best practice). In addition, EPA also made the following points:

1. Family housing should be retested every 5 years and large buildings after every mechanical adjustment (e.g., HVAC systems).
2. EPA reemphasizes that mitigated buildings need to be retested at least every 2 years.
3. New residential construction should be tested before occupancy.
4. Radon action levels in the workplace are the same as those recommended in family housing (i.e., ≤4 pCi/L).
5. High-efficiency particulate air (HEPA) filtration is not recommended as a mitigation method.
6. Preconstruction radon predictions (i.e., soil flux measurements) and the use of radon test data from neighboring areas should not be considered substitutes for radon testing after construction has been completed.
7. RRNC practices are recommended for all new construction within EPA Radon Zones 1 and 2 (Figure 4).

3. OVERVIEW OF RADON TESTING

3.1 RADON TESTING STANDARDS

It is important to note that in 2012, EPA initiated a voluntary consensus-based standards initiative with the radon industry (https://www.epa.gov/radon/radon-standards-practice). The subsequent standards produced by this partnership have superseded and consequently replaced the previous EPA standards and guidance documents. Consequently, for this version of the guidebook a comprehensive review was performed and where applicable, changes were made to the NAVRAMP testing protocol. Therefore, for testing standards references to be utilized in a statement of work, requests for proposal, performance work statements and similar types of documents use this document, *Navy Radon Assessment and Mitigation Program Guidebook for Naval Shore Installations* (2021) and consult the list in Table 5. These standards can be viewed or purchased on-line at https://standards.aarst.org/ .

3.2 RADON MEASUREMENT TESTING DURATION

Within the United States, radon testing is divided into two distinct types of measurements: short term (2 to 90 days) and long term (91 to 365 days). The advantage of short-term measurements is that radon data can be collected quickly. In addition, because detectors are in the field for less time, the potential for field attrition is much lower. With respect to accuracy and cost, both types of measurements are comparable. However, unlike the levels of most pollutants, indoor radon levels are constantly changing. Studies by EPA and DOE have found that indoor radon levels can vary by as much as a factor of 10 from one season to another. Other studies have shown that the indoor concentration of radon can increase by a factor of 2 to 10 during short-duration weather events (e.g., rain, periods of high winds, and cold snaps; see Figure 6). Because of these variations, EPA bases the health risks of radon exposure on an integrated annual average. When a short-term test is performed, EPA recommends that the measurement be performed under closed building conditions, which means that in a heating climate, the test should be performed ideally at the season midpoint with the building closed (e.g., windows and doors kept always closed) and not during periods of abnormal weather conditions. In addition, if the test is <4 days in duration, the building must be closed for at least 12 h before the placement of the testing device.

A long-term measurement offers the advantage of integrating the impact of short-duration weather effects over a longer time period. Also, a long-term measurement can be performed during normal living conditions, thus minimizing the impact of radon testing on either work or living activities.

Table 5. Current radon testing standards

Standard Name	**Standard Number**	**Applicability**
Protocol for Conducting Measurements of Radon and Radon Decay Products in Homes	ANSI/AARST MAH-2019	This standard of practice specifies minimum requirements and general guidance for measuring radon concentrations in single-family residences. This standard applies to testing structures whether conducted for real estate or non-real-estate purposes. The purpose of test protocols is to consistently produce, to the extent possible, reliable, and repeatable radon measurements. Radon measurements are conducted to determine if radon mitigation is necessary to protect current and future occupants.
Protocol for Conducting Measurements of Radon and Radon Decay Products in Multifamily Buildings	ANSI/AARST MAMF-2021	This standard of practice specifies procedures and minimum requirements when measuring radon concentrations in shared structures, or portions of shared structures, used for residential, non-residential, or mixed-use purposes to determine if radon mitigation is necessary to protect current and future occupants.
Protocol for Conducting Measurements of Radon and Radon Decay Products in Schools and Large Buildings	ANSI/AARST MALB-2021	This standard of practice specifies procedures and minimum requirements when measuring radon concentrations in shared structures, or portions of shared structures, used for residential, non-residential, or mixed-use purposes to determine if radon mitigation is necessary to protect current and future occupants.

Because of these and other considerations, EPA recommends that any radon test be performed for as long as possible to provide the most accurate representation of the annual average. Because corrective action can be expensive, EPA recommends that follow-up measurements be performed in cases where elevated radon levels were detected and in cases when abnormal weather occurred during the test period. Generally speaking, the higher the initial radon result, the more confidence one has that elevated radon levels are present. For example, if the initial radon result is ≥8 pCi/L, EPA recommends immediate short-term measurements be performed or mitigation performed (EPA January 2009, 402/K-09/001).

3.3 NAVRAMP VS. CURRENT TESTING PROTOCOLS

Within the United States, approximately 95% of all residential radon testing is performed in conjunction with a residential real estate transaction. Consequently, there is considerable pressure to get a home tested as quickly as possible to avoid mortgage closing delays. For this reason, historical EPA protocols and the current real estate testing protocol (ANSI/AARST MAH-2019) allows for a single, collocated duplicate measurement or a single continuous monitor with hour resolution of at least 48 h in duration under closed building conditions. If the measurement was performed correctly, then a follow-up test would not be required with the mitigation question resolved as a pass (radon levels < 4 pCi/L) or fail (radon levels ≥ 4 pCi/L) proposition. In the development of this testing protocol, it was acknowledged that radon levels can vary significantly from day to day or season to season and that the short-term measurement although an accurate representation of the radon levels during the test period, it would not necessarily be representative of the true annual average radon concentration. However, in cases of a false positive (e.g., the test result was ≥ 4 pCi/L but the annual average was < 4 pCi/L) it was concluded that radon mitigation even at 2 pCi/L provides some health benefits. With respect to false negatives (e.g., the test result was < 4 pCi/L but the annual average was ≥ 4 pCi/L) it was assumed that the new homeowners would follow EPA's and the radon industry's recommendation to perform a follow-up test later.

With respect to the other 5% of residential testing (commonly called the *Citizens Guide to Radon* protocol or informed consumer radon test) EPA recommends a phased approach to radon testing using an initial short-term test followed by either a second short-term test or a long-term test if the initial result was ≥ 4 pCi/L (EPA402/K-12/002|2016|). If the long-term test was selected, it was recommended to test for as long as practical. The basis for radon mitigation being the average of the two short-term tests or the single long-term measurement being ≥ 4pCi/L. Although this approach does address false positive short-term radon tests, it does not address the potential for a short-term false negative.

In 1988 working with EPA and DOE, the Navy developed an initial NAVRAMP testing protocol for both residential and nonresidential buildings. The developed protocol mirrored the informed consumer test (one detector per testing location) using an initial long-term test of up to 1 year in duration. If elevated radon levels were found, a short-term test was then performed under the best single seasonal closed building conditions to confirm the presence of elevated radon prior to mitigation. However, implementation of this protocol revealed several problems. For one, the timing of the confirmation test was critical, meaning that funding and other logistics had to be in place to measure during a particular seasonal window. If not, then the test would be postponed. The second issue was the delay in performing corrective action. In some cases, residents and occupants had to wait 2-3 years for the confirmation test to be performed thus increasing the potential risks from exposure to elevated radon levels. The third issue was overall costs. Confirmation testing required a second and, in some cases, a third round of mobilization/demobilization which added to the overall costs of testing an installation for radon. If the confirmation test failed to confirm elevated radon, then a follow-up test was performed, and the conclusion based upon the follow-up test.

In 1997, NAVFAC Pacific working with DOE evaluated different testing approaches in the field which would reduce the timeline for corrective action and save money. Key considerations for these studies were to the best extent possible incorporate key elements and precedents of the existing EPA testing protocols. These elements were:

- Real Estate Testing Protocol
    - Use collocated duplicates
    - Base the testing conclusion on the average of the two collocated results
- Citizens Guide Testing Protocol
    - Test for as long as practical

Field evaluations using this approach found that the time and costs for placement, retrieval, data entry, processing and reporting were not significantly impacted using collocated duplicates. In fact, the costs for procurement of the second detector were less than the projected costs for confirmation testing. An added benefit to this approach was the ability to inform the resident or occupant of conclusive radon test results without the need for further testing.

Another evaluated consideration was the probability of two collocated detectors which provided bad test results within the established EPA precision range for duplicate radon results ≥ 4 pCi/L. An evaluation of historical NAVRAMP collocated duplicate test data, and data sets provided by the Army and Air Force found that for long-term, collocated duplicate alpha track detectors the failure rate was about 1 in 10,000 measurements.

The conclusions of these studies were that performing 100% collocated duplicates with proper quality assurance and quality control (QA/QC) would eliminate the need for mandatory confirmation tests and would greatly speed up mitigation planning and execution. These recommendations were incorporated officially into the NAVRAMP in 2015.

3.3.1 Radon Testing in Family Housing

During the late 1980s the accepted approach in radon testing in multi-family housing (duplex, triplex, quadplex etc.) was to test one or 10% of the testable units (which ever was greater) per building. The assumption being that if one unit in the building had elevated radon, they all would. However, during 1989-1991 the Navy and DOE performed a series of studies to evaluate this assumption. These studies showed conclusively that this approach missed up to 90% of the units with elevated radon within a given population (Section 1.3.4). For this reason, in 1991 the NAVRAMP residential testing during was changed to include all testable family housing units at an assessment location. It is important to note that the basis of the current industry multi-family testing standards relies upon these Navy studies.

An examination of family NAVRAMP housing data (Table 6) collected at installations with known elevated radon potential demonstrates this fact. As can be seen in Table 6, despite the presence of elevated radon potential at each site sampled, none of the townhouse buildings had elevated radon within all units of the building. Therefore, a statistical sampling approach that samples only one or two units of a fourplex building would miss the units with elevated radon most of the time. A similar conclusion can be reached with respect to duplex buildings: Table 6 shows that Site 1 only had 3 of 61 buildings (5%) with elevated radon in both units. So, if only one unit was sampled in the duplex for all practical purposes, half the units with elevated radon would not have been tested.

It is important to note that finding elevated radon in all units within a multifamily building is not unheard of. For example, in one survey of buildings with similar characteristics to those in Table 6, 34 of 36 buildings (300 units) had elevated radon in every unit in the building. In another survey, 5 of 35 buildings (140 units) had elevated radon in all units. In summary, like the case of single detached units, there is no known way to predict in advance if a particular home has elevated radon. Multifamily housing is no different. The only way to know if elevated radon is present is to test each testable unit in a building.

Residential studies by DOE, EPA, Navy and others have shown that on the same floor level, the radon concentration does not vary significantly from room to room in most single-family homes. Therefore, it is unnecessary to test every ground contact room in family housing. However, in larger quarters which have multiple air handlers or are divided into separate sections (e.g., formal gathering room, office, maids' quarters, etc..) testing in more than one location may be required.

Table 6. Single vs. multifamily housing radon survey data

Site 1	**Single detached**	**Duplex**	**Townhouse**	**Total/ average**
Number of units sampled	165	122	120	407
Number of buildings	165	61	30	256
Number of units ≥4 pCi/L	14	26	13	53
Percentage of units ≥4 pCi/L	8%	21%	11%	13%
Number buildings with 2 units ≥4 pCi/L	N/A	3	2	5
Number of buildings with all units ≥4 pCi/L	N/A	3	0	3
Highest single result (pCi/L)	66.7	8.5	26.3	2.3
Site 2	**Single detached**	**Duplex**	**Townhouse**	**Total/ average**
Number of units sampled	70	510	247	827
Number of buildings	70	255	38	363
Number of units ≥4 pCi/L	0	14	57	71
Percentage of units ≥4 pCi/L	0%	3%	23%	9%
Number buildings with 2 units ≥4 pCi/L	N/A	0	4	4
Number of buildings with all units ≥4 pCi/L	N/A	0	0	0
Highest single result (pCi/L)	3.3	9.3	27.1	2.3
Site 3	**Single detached**	**Duplex**	**Townhouse**	**Total/ average**
Number of units sampled	60	120	852	1032
Number of buildings	60	60	213	333
Number of units ≥4pCi/L	1	2	51	54
Percentage of units ≥4 pCi/L	2%	3%	6%	5%
Number of buildings with 2 units ≥4 pCi/L	N/A	0	2	2
Number of buildings with all units ≥4 pCi/L	N/A	0	0	0
Highest single result (pCi/L)	4.4	6.5	36.7	1.5

For single family homes, the NAVRAMP testing protocol is consistent with the current industry standard (ANSI/AARST MAH 2019). However, NAVRAMP does require additional quality control and tests using 100% duplicate detectors.

With respect to the current multi-family housing industry testing standards (ANSI/AARST MAMF-2021), the NAVRAMP testing protocol is consistent with the noted exception of the number of quality control detectors (NAVRAMP is more stringent), upper floor radon testing and apartment buildings with centralized HVAC systems. Over the past 15 years, high rise condominiums and apartment buildings have been identified with elevated radon levels within units not in ground contact. In one case the units were located on the 6th, 7th and 8th floor. Investigations into the cause have found that these units had very low natural ventilation and had been constructed with concrete containing a higher-than-average amount of naturally occurring radium and thorium. In none of the cases cited did an upper floor unit have elevated radon levels emanating from the soil without the ground contract unit directly under it testing ≥ 4 pCi/L. A closer look at the high-rise study finds that the radium and thorium concentrations within the concrete vary significantly from location to location within a unit. Although the ventilation rates in these units were virtually identical, not all units on a particular floor were found to have elevated radon levels. The deciding factor being the overall percentage of higher-than-average radium and thorium within a particular unit. Because of these findings, the ANSI/AARST multi-family standards require that for units not in ground contact, one and not less than 10% of the units per floor be tested. Under NAVRAMP, upper floor testing is not required unless it is suspected that the units have < 0.3 air-exchange per hour (ACH) and that the concrete (wood frame buildings are not an issue) may contain above average radium and/or thorium content. If this is suspected, then all units in the apartment building will need to be tested.

With respect to apartment buildings with centralized HVAC systems, the problem revolves around inconsistent ventilation rates within the individual rooms of a unit. The root cause of the problem is that the apartment occupant has adjusted the supply air coming into the various rooms to improve personal comfort or reduce noise. Typically, these type of HVAC units do not have a thermostat for the occupant to adjust and may only have an on/off switch. In this type of HVAC system, it is not uncommon to find only one room (typically a bedroom) with elevated radon levels. Therefore, the ANSI/AARST MAMF-2021 requires that all routinely occupied rooms in the unit be tested (e.g., all bedrooms, family room, eating area etc.). Although a significant number of tower type apartment buildings are present within Navy and USMC housing, most are equipped with an individual unit thermostat, and some have variable air volume supplies which allow the occupant the ability to make the needed comfort adjustments without causing a supply imbalance. Therefore, NAVRAMP testing is only required in one location per unit. However, if the problems noted above are observed, then testing in all ground contact rooms would be required.

3.3.2 Radon Testing in Nonresidential Buildings

Since the early 1990s it has been recognized that the distribution of radon levels within nonresidential buildings varies significantly from room to room. For this reason, in 1993 EPA (EPA, July 1993) recommended that all occupied rooms in ground contact be tested. A good example of this is NAVRAMP test data collected at one naval installation found that within 129 nonresidential buildings identified as having elevated radon levels, most of the time, elevated radon was found in ≤20% of the rooms sampled (Figure 9). Since that time, studies performed by the Navy and USMC found that 50% of the time the building mechanicals (e.g., supply, exhaust, and return) and localized ventilation issues played a direct role in causing the elevated radon levels in the room (Figure 10). However, application of this knowledge with respect to testing fewer rooms within a given building proved difficult for the simple reason being that the required mechanical diagnostics are more expensive than testing the building for radon.

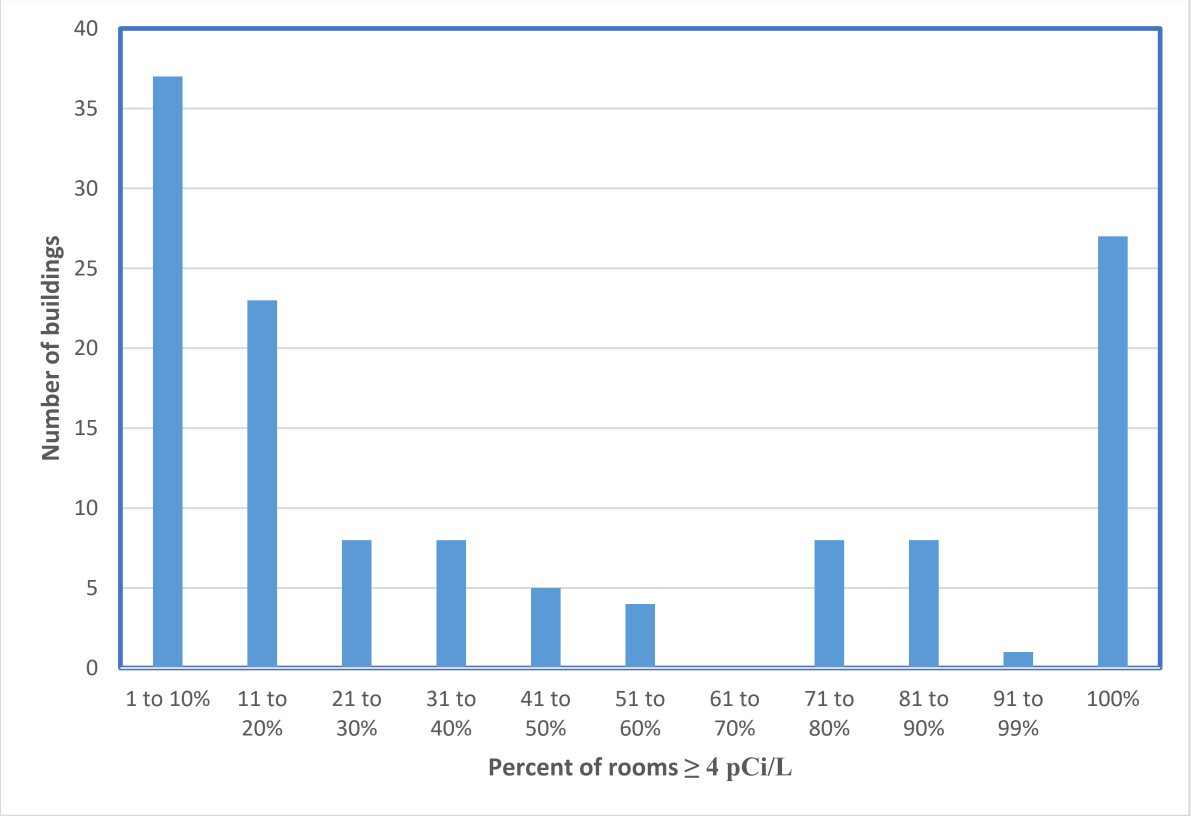


Figure 9. Percentage of rooms ≥4 pCi/L in 129 buildings with six or more rooms.

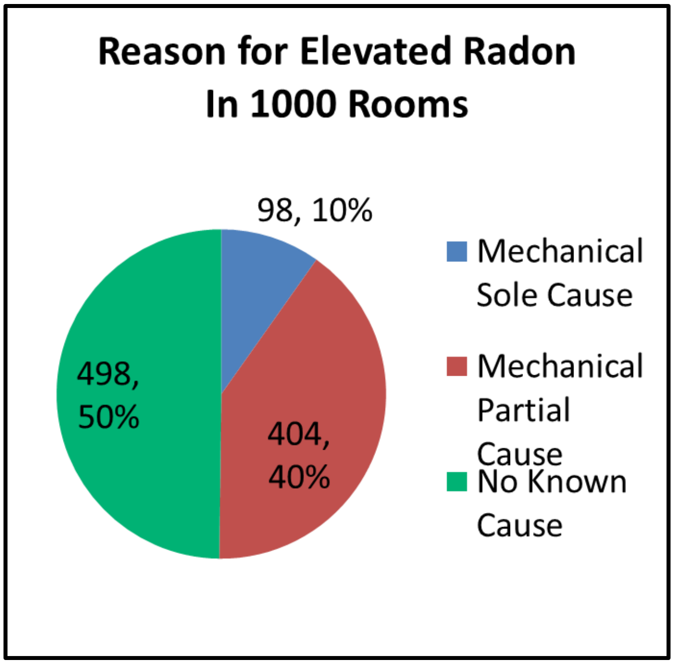


Figure 10. Mechanical impact on radon levels in nonresidential buildings.

With respect to the current large building industry testing standards (ANSI/AARST MALB-2021), the NAVRAMP testing protocol is consistent with testing all occupiable and readily occupiable spaces on the ground floor. However, NAVRAMP does not require upper floor testing (one room or 10% whichever is greater) in randomly selected rooms (see Section 3.3.2 for NAVRAMP rationale) and has more stringent quality control.

Another key difference between the NAVRAMP and the industry large building testing standard is within low density occupancy rooms ≥ 10,000 ft^2 testing is performed at an interval of one sample location per 5,000 ft^2 up to a maximum of 5 testing locations per room whereas the industry standard is set at one testing location per 2,000 ft^2 with no upper limit. Studies by the Army, Navy and USMC in large rooms have found that the 2000 ft^2 interval although effective at mapping out an elevated radon plume to be excessive with respect to determining elevated radon potential within the room. If elevated radon levels are found, then diagnostic radon measurements prior to mitigation (if needed) can be performed (NAVRAMP Guidebook Section 3.2.9.5) to map out the plume.

3.3.3 Basis Of NAVRAMP Quality Assurance and Quality Control

In response to the requirements in the 1988 IRAA, EPA released an updated version of the *Citizen's Guide* and provided to its sister agencies additional guidance on how to conduct a radon testing program. This guidance also included minimum criteria for quality assurance and quality control (QA/QC) for radon testing within federal buildings (most of these recommendations were eventually incorporated in EPA July 1993, 402-R-92-014). Specifically, the document called for each building tested to have

- blanks (5% or 25, whichever was smaller)
- collocated duplicates (10% or 50, whichever was less)
- spikes (no limits were provided, but 3% was recommended in the reference document)

For analysis of the QC data, EPA stated that the procedures presented in *Indoor Radon and Radon Decay Product Measurement Device Protocols* (EPA-520/1-89-009) should be used. However, in 1992, this document was superseded by EPA 402-R-92-004 (EPA July 1992).

For blanks, EPA requires monitoring of the background exposure that may have accumulated during shipment and storage of the testing devices. Because each type of radon testing device (e.g., ATD, charcoal, or electret ion chamber) responds differently to background exposure, the EPA protocol provides device-specific corrective action if a reading is found to be significantly greater than the lower level of detection. For example, for electret ion chambers (EICs), EPA requires that 5% of the EICs or 10, whichever number is smaller, be set aside to track voltage drift. Over a 3-week test period for the EICs, any voltage loss found in the control EICs of more than 1 V per week should be investigated. In addition, because EICs are sensitive to background gamma radiation, a correction must be multiplied by the gamma radiation level at the site (in µR/h) and the product (in equivalent pCi/L) subtracted from the apparent radon concentration. If the gamma radiation at the site is unknown, then a measurement would need to be performed directly using appropriate radiation detection instruments.

The objective of performing simultaneous or duplicate measurements is to assess the precision error of the measurement method, or how well two side-by-side measurements agree. This precision error is the “random” component of error (as opposed to the calibration error, which is systematic). The precision error, or the degree of disagreement between duplicates, can be composed of many factors. These include the error caused by the random nature of counting radioactive decay, slight differences between detector construction (for example, electret chamber volume), and differences in handling of detectors. With respect to collocated duplicates, EPA recommends using the relative percent difference (RPD, Eq. [2]) as the best indicator of overall precision in radon measurements.

$$\text{Relative percent difference} = \frac{(\text{Highest pCi/L} - \text{Lowest pCi/L}) \times 100\%}{\text{Mean}}$$

Equation 1. Relative percent difference

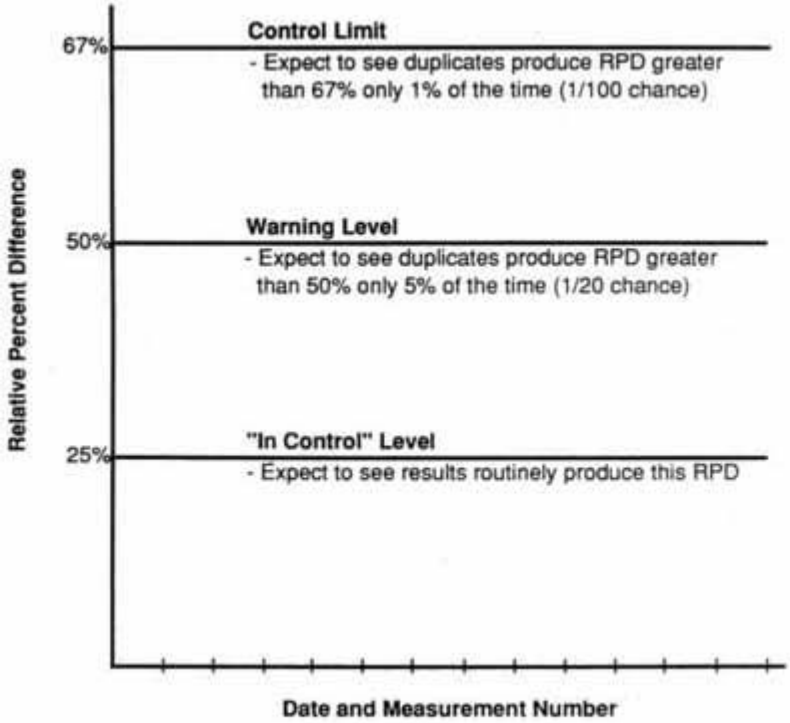
(from *Quality Assurance Handbook for Air Pollution Measurement Systems: Volume I,*
EPA 600/9-76-005 [EPA 1984])

Ideally, the results of duplicates should be assessed in a way that allows for determining the level of chance associated with a particular difference between duplicates. This will allow for the predetermination of limits for the allowable differences between duplicates before the cause of large differences is investigated. For example, the warning level, or the level of discrepancy between duplicates that triggers an investigation, may be set at a 5% probability. This level is a difference between duplicates that is so large that, when compared with previous precision errors, should be observed only 5% of the time. A control limit, at which further measurements should cease until the problem is corrected, may be set at 1% probability.

A control chart for duplicates is not as simple as a control chart used to monitor instrument performance, as for a check source. This is because the instrument's response to a check source should be constant with time. Duplicates are performed at various radon concentrations, however, and the total difference between the two measurements is expected to increase as radon levels increase. Because of the difficulties in measuring radon at low levels, EPA guidelines recommend that the acceptance criteria be based on the average of the two results relative to 4 pCi/L. After the RPD is calculated, its value is plotted on one of the two applicable control charts by date and average radon concentration (Figures 11 and 12). Over time, the RPDs are evaluated based on the overall number of results within the respective ranges (i.e., in control, warning level, and control limit). If the number of data points exceeds what would be predicted at the warning level, then investigation into the cause of the problem is warranted. However, if a significant number of data points are at or beyond the control limit, then measurements should cease until the problem has been identified and corrected.

EPA provides a statistical table (Table 7) for determining what constitutes a significant number of RPD warnings and failures. The required action is based upon the number of failures and the total number of data available. For example, if two sets of duplicates had RPDs outside the warning level, and between 2 and 7 sets of data were within the control limit, EPA would recommend that analysis stop until the problem had been identified and corrected. However, if between 8 and 19 sets of acceptable data had been obtained, it would be necessary only to investigate the problem.

Control Chart* for Relative Percent Difference (RPD)
Based on an "In Control" Level of 25% (=COV of 18%)
(For duplicates where average <4 pCi/L or 0.02 WL)



RPD=difference between two measurements divided by their average

Example: Detector A=2 pCi/L, B=3 pCi/L, RPD=40%

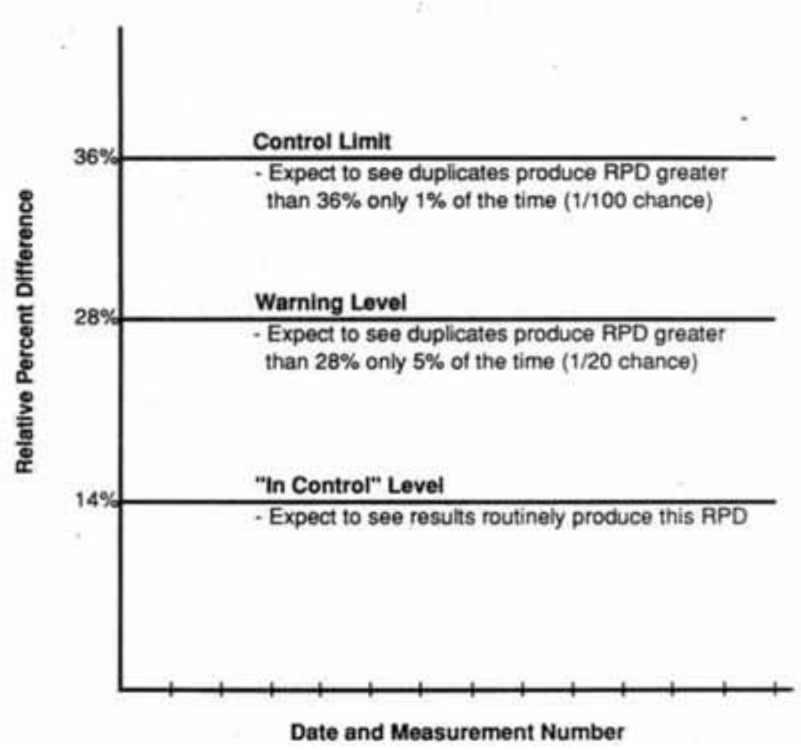
If RPD exceeds the *control limit*—cease measurements until the problem is identified and corrected.

If RPD exceeds the *warning level*—follow guidance in *Section B.3* and see Exhibit B-5 within *Protocols for Radon and Radon Decay Product Measurements in Homes* (EPA 1993, 402-R-93-003)

Figure 11. Control chart for RPD for average radon results <4 pCi/L.

(*Protocols for Radon and Radon Decay Product Measurements in Homes* [EPA May 1993])

Control Chart* for Relative Percent Difference (RPD)
Based on an "In Control" Level of 14% (=COV of 10%)
(For duplicates where average ≥ 4 pCi/L or 0.02 WL)



RPD=difference between two measurements divided by their average

Example: Detector A=5 pCi/L, B=6 pCi/L, RPD=18%

If RPD exceeds the *control limit*—cease measurements until the problem is identified and corrected.

If RPD exceeds the *warning level*—follow guidance in *Section B.3* and see Exhibit B-5 within *Protocols for Radon and Radon Decay Product Measurements in Homes* (EPA May 1993, 402-R-93-003)

Figure 12. Control chart for RPD for average radon results >4 pCi/L.

[*Protocols for Radon and Radon Decay Product Measurements in Homes* (EPA May 1993, 402-R-93-003)]

Table 7. Criteria for taking action for measurements outside the warning level[a]

Number of duplicate results outside the warning level	**Total number of duplicates**	
	Investigate, but continue operation **A**	**Stop operation until problem is corrected** **B**
2	8–19	2–7
3	17–34	8–16
4	29–51	17–28
5	41–67	29–40
6	54–84	41–53
7	67–100	54–66

[a] Modified from Goldin (Goldin 1984) and based upon cumulative probability tables of the binomial distribution.

Protocols for Radon and Radon Decay Product Measurements in Homes (EPA May 1993, 402-R-93-003).

EPA addresses spikes by requiring laboratories (organizations that read electrets are considered laboratories) to maintain a performance ratio (Eq. [3]) between 0.75 and 1.25. If the performance ratio is outside the range, EPA recommends that the measurement cease until the problem has been identified.

$$\textbf{Performance Ratio} = \frac{\textbf{(Mean Measured Value)}}{\textbf{Target Value}}$$

Equation 2. Performance ratio

3.4 TYPES OF RADON GAS DETECTORS

EPA and ANSI/AARST divide short-term measurement devices into two categories, continuous and integrating. By definition, continuous radon monitors (CRMs) must have the ability to integrate, record and be able to produce reviewable and retrievable readings with 1 hour resolution. In addition, they must also possess the ability to be recalibrated periodically. Under the current standards, CRMs can measure gas or progeny (progeny monitor are not allowable under NAVRAMP). However, those that measure gas concentrations are the most popular and most common. Integrating devices average the radon exposure by absorption, physical damage to a film, or the loss of surface electrical potential. A key difference between integrating devices and continuous devices is that after the measurement has been performed, integrating devices are analyzed in an off-site laboratory. If integrating devices are used in high-priority, short-term measurements (e.g., real estate transactions or confirmation measurements), EPA and ANSI/AARST recommend that the measurement be performed with collocated duplicate detectors. Common examples of integrating radon detectors for short-term measurements are alpha tracks, charcoal canisters and electrets. More recently electronic integrating monitors (EIM) have become commercially available. EIM monitors measure alpha particles using a silicon photo diode chip. When the alpha particle hits the photo diode, a small signal current is generated. Because the counting efficiency of these chips (counts per minute per pCi/L) is low, this device cannot provide hourly measurements. But, by summing the accumulated counts over days or weeks, an accurate radon measurement can be determined.

Under NAVRAMP, all radon monitors and detectors used for reportable measurements must be approved by a certifying body (NRSB or NRPP). A list of approved devices can be found at https://nrpp.info/devices/approved-devices/ or https://www.nrsb.org/wp-content/uploads/2019/04/NRSB-Approved-Devices.pdf .

3.4.1 Continuous Radon Monitors

Continuous radon monitors (CRMs) typically measure radon gas or radon decay products in air. These measurements are performed in real time, meaning that the radon concentration can be measured and studied at fixed time intervals. To measure radon, room air is either pumped or diffused into a counting chamber that detects the ion particles generated by the radioactive decay of radon and its progeny. The counts per unit of time measured by the detector are then transmitted to a recording device (electronic or printer), where they are converted into picocuries per liter. The typical exposure period for CRMs, as for most short-term devices, is 2 to 7 days. If used properly, CRMs are the most accurate of all short-term radon measurement devices. For example, most commercially available instruments are typically within 5% of the true radon concentration (vs. 15 to 25% for integrating devices). However, the disadvantage is the high initial purchase cost, $500 to $25,000 per CRM. Also, CRMs must be maintained and require periodic calibration. As a general rule, measurements performed by radon professionals using CRMs are more expensive than those using integrating detectors.

There are three general types of CRMs:

1. Scintillation Cell and Photomultiplier Tube
    - Radon is actively drawn (e.g., have a pump) through a filter into a cell where the decay of Radon-222 and the subsequent Polonium-218 and Polonium-214 produce alpha particles which impact with a zinc sulfide coating on the wall of the cell. The impact of these alpha particles creates small burst of light which are then detected by a photomultiplier tube. The photomultiplier tube then produces electrical pulses which are then counted.
2. Pulse Ion Chamber
    - Radon diffuses into the instrument counting chamber where the alpha decay of Radon-222, Polonium-218, and Polonium-214 create ions in air which are in turn counted on an electrically charged sensor. The drop in voltage on the sensor is proportional to the radon concentration.
3. Solid State Silicone Chip
    - Radon diffuses into the instrument counting chamber where the alpha particles produced by the decay of Radon-222, Polonium-218, and Polonium-214 impact with a solid-state silicon chip. The impact of the alpha particles on the solid-state chip cause electrical pulses which are then counted.

Each of the different types of CRMs have its strengths and weaknesses. For example, active scintillation cell monitors have very rapid response times (e.g., ~ 5 minutes) with no time lag with respect to changing radon levels. But, because of diffusion considerations, pulse ion chambers and solid-state chip monitors may lag 1 to 4 hours behind the current radon level. Therefore, what is reported by the CRM at 1100 may have occurred at 0800. For routine radon measurements this lag is not a problem. However, if diagnostic measurements are being performed (Section 5.1.9) knowing the lag time for a particular instrument is crucial to establish cause and effect.

With respect to sensitivity (counts per minute per pCi/L) scintillation cells have about 3 to 5 times the sensitivity of pulse ion chambers or solid-state silicone chips which provides more counts per measurement resulting in better accuracy. The disadvantage of scintillation cells is the high initial purchase and operating costs compared to the other two types. For one, scintillation cells must be purged with dry air or nitrogen after each use. Also, over time, the radiological background of scintillation cells will increase which will require them to be replaced or taken out of service for weeks or months. Therefore, for extended operations, a supply of additional calibrated cells would be needed. To maintain certification, all CRMs are required to be returned to the manufacturer for recalibration once every year.

Radon levels are rarely constant in nature or the indoor environment. Common reasons for this variation are season and episodic weather such as wind, rainfall and barometric pressure and outdoor vs. indoor temperature. However, in most buildings (not all) during a 24 h period radon levels also go through a diurnal cycle in which the radon levels tend to be at their minimum during the midafternoon and their highest within a few hours after midnight (Figure 13). The difference between the minimum and maximum radon levels during this 24 h cycle can range from a few percent (Figure 13) to orders of magnitude (Figure 14) higher. This cycle is unique for each individual housing unit and nonresidential room and may change depending upon the season or HVAC settings.

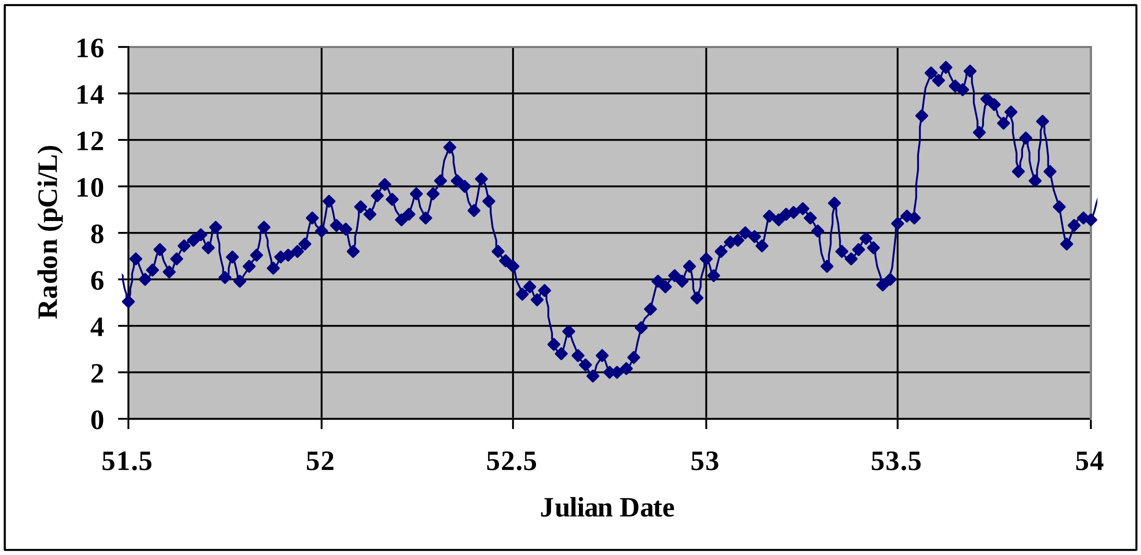


Figure 13. Example of a slight diurnal radon pattern.

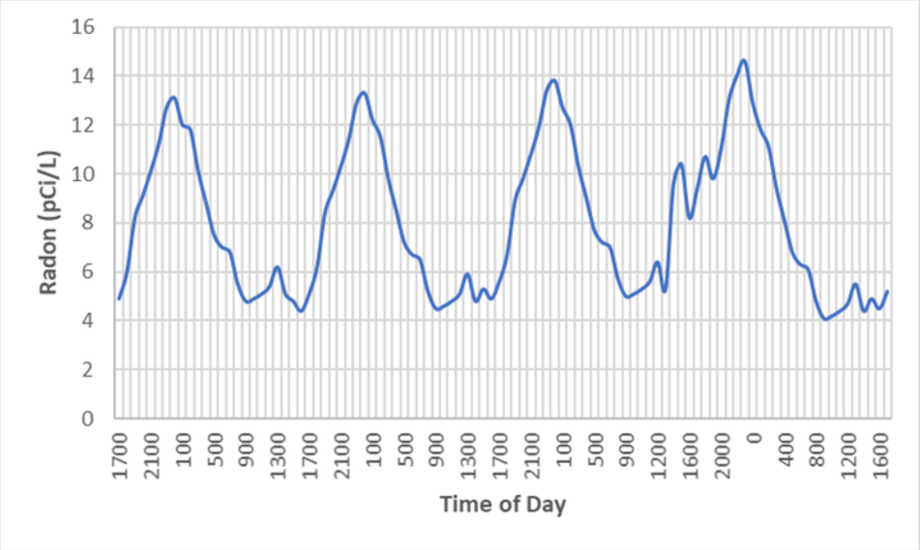


Figure 14. Example of a strong diurnal radon pattern.

The chief advantage of CRMs over passive devices is the ability to “see” what is occurring by recording radon concentration as a function of time. When the instrument is downloaded and the data plotted, the impact of episodic weather events, other nonstandard tests (e.g., doors and windows left open) and building mechanical cycles can be measured and quantified. With respect to episodic weather patterns, rain can result in sharp and unpredictable increases in radon levels (Figure 6). In most buildings, spikes because of rain are very typical and it is not unusual in homes with annual radon levels of < 2 pCi/L to have rain spikes in excess of 10 pCi/L (Figures 15 and 16). Another episodic weather event is wind speed and wind direction. During a tropical storm in Guam (20 to 30 mile per hour sustained winds) a CRM plot (Figure 17) showed enhanced radon levels with the wind blowing from the northeast. However, when the depression moved further north, and the wind direction changed to northwest radon levels dropped to < 4 pCi/L. Once the depression had passed, and the wind direction became variable, the normal radon pattern returned. Looking at available geological maps, it was determined that the building was located on an 800 ft high karst limestone plateau (Section 1.2.3). Cave openings on the north and northeast side of the island allowed wind to push the radon up into the building. The northwest side did not have any cave openings so there was no wind effect.

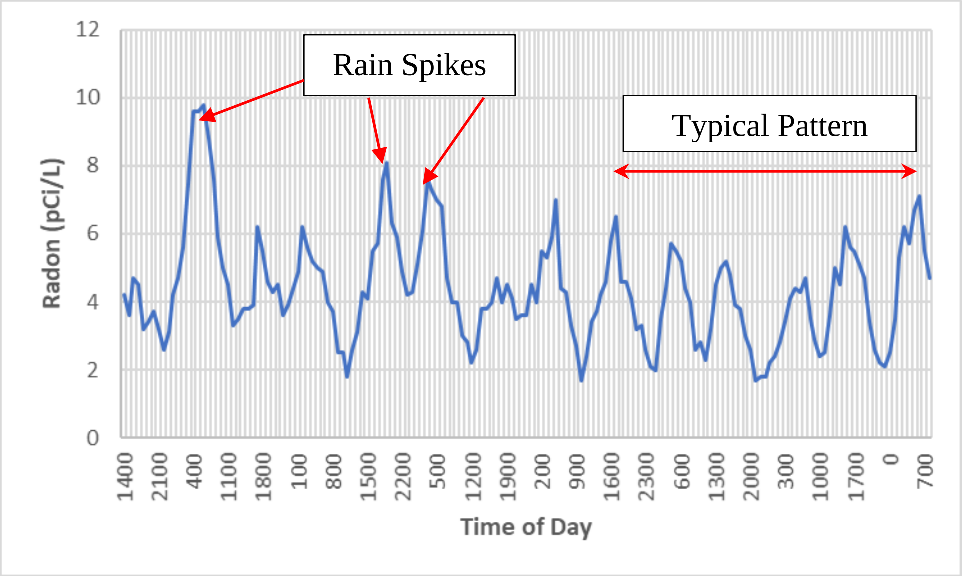


Figure 15. Rain spikes

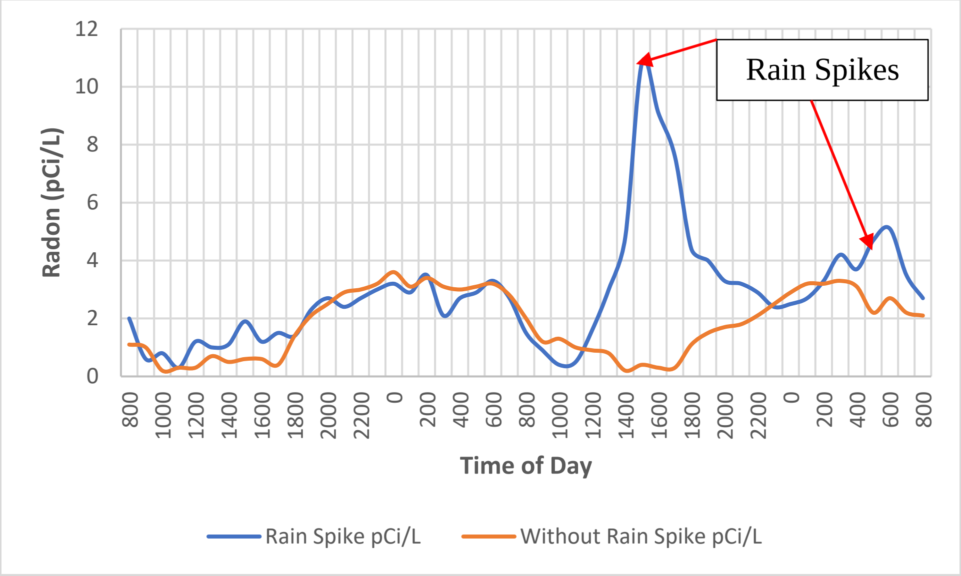


Figure 16. Home radon levels with and without a rain spike.

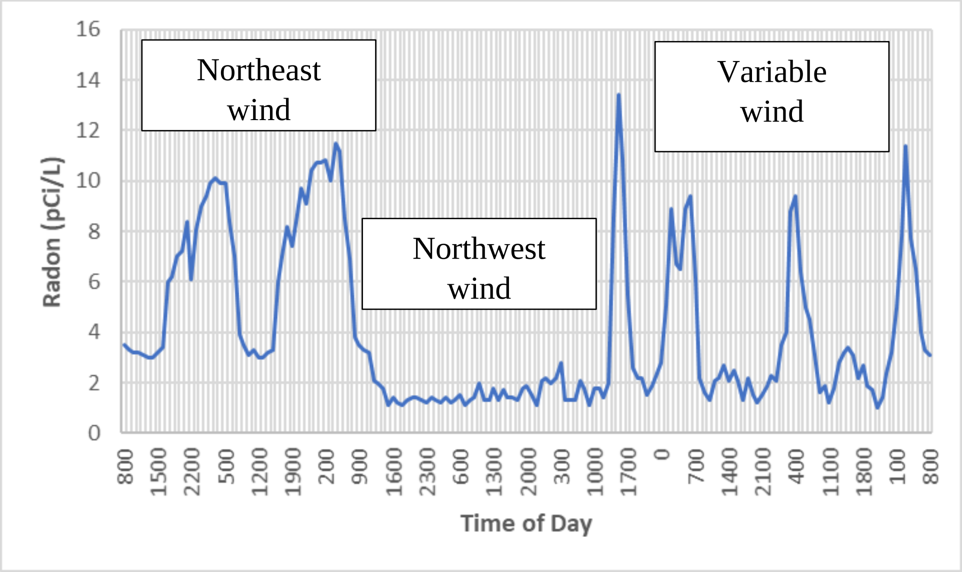


Figure 17. Radon and wind direction.

A rare patten is called a sea tidal pattern in which the indoor radon levels are dependent upon the tides (Figure 18) within karst geology. In long-term measurements these types of events are averaged out over the test period. For example, in Figure 18 the annual average for the housing unit was 5.1 pCi/L vs. 4.4 pCi/L for the entire CRM test period. However, if the CRM measurement was performed only during the last 48 h, the result, 3.9 pCi/L may have indicated that radon mitigation was not required. For this reason, NAVRAMP always defers to the long-term measurement as being more representative of the annual average radon level.

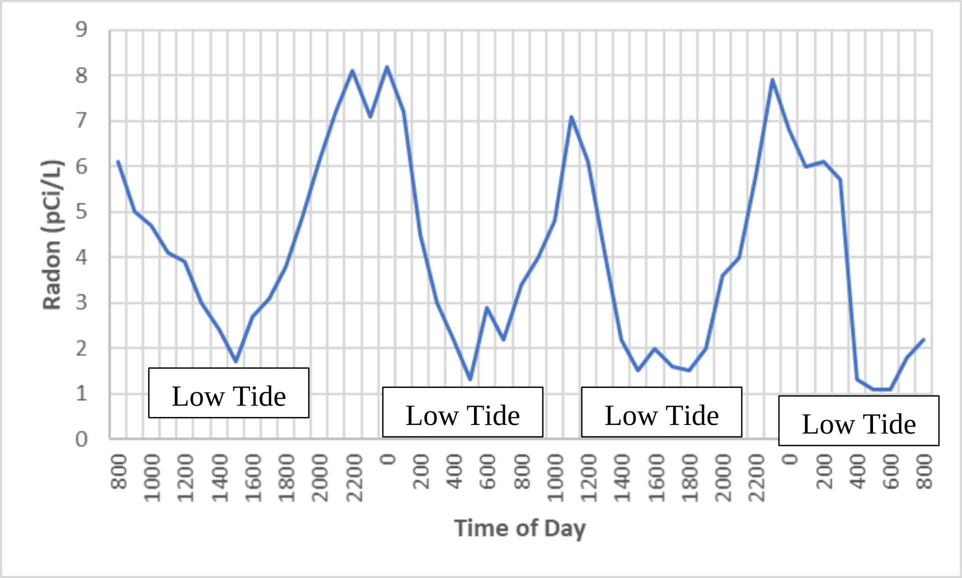


Figure 18. Radon levels caused by ocean tides.

With respect to HVAC mechanical systems in nonresidential buildings, CRMs are very useful in measuring the impact of certain mechanical features on the radon levels. For example, in Figure 19 it was suspected that the exhaust blower for the building was causing the elevated radon levels. To measure its potential impact the exhaust blower was turned off, operated intermittently on a timer and left on. The plot shows conclusively that the exhaust blower was the cause. Additional information on diagnostic CRM measurements in buildings with HVAC systems has been included in Section 5.1.9.

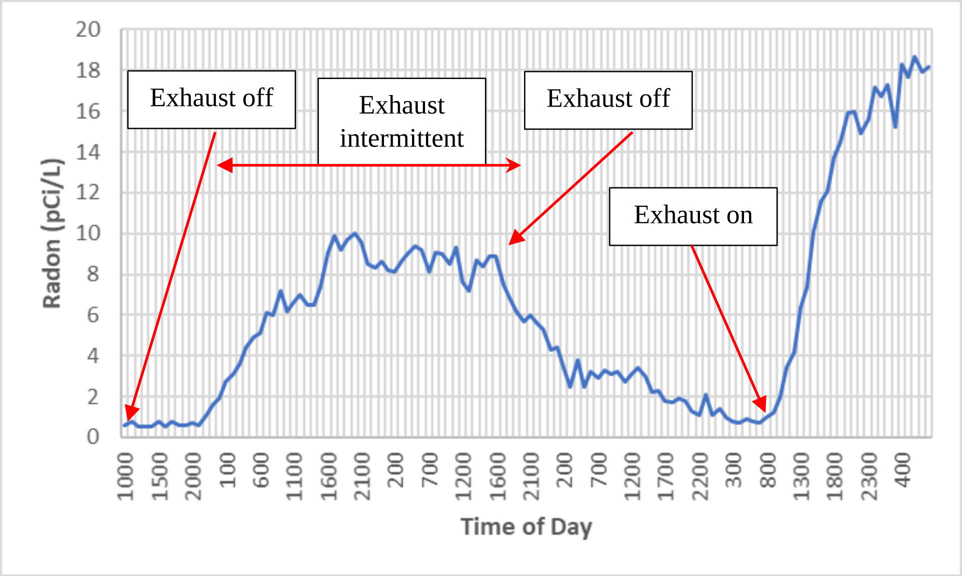


Figure 19. Impact of exhaust blower operation on radon levels.

CRMs can also be used to monitor the effectiveness of a newly installed radon mitigation system. In Figure 20 an SSD system was installed in a very low permeability subslab material. The CRM measurement was performed in order to see in “real time” if the proposed system was going to be effective or if additional suction points would be required. As can been seen in Figure 20 the radon levels began dropping almost immediately after the system was activated. In addition, the plot shows the importance of waiting at least 24 h prior to performing the postmitigation test. As a side note, there was no discernable diurnal pattern in this room.

It is important to note that the availability of CRMs within the radon industry is finite. Currently, most radon testing companies are instrumented to provide a fast turnaround for the real estate market. Consequently, the number of instruments that they lease or own is geared towards their market with < 30 instruments on average. Also, as a general rule, companies charge more for routine CRM measurements (e.g., 48 h measurements) and considerably more for a 7-day test. Thus, the logistics and cost of performing hundreds of CRM measurements within a short period of time would be very challenging. Therefore, the use of short-term, passive detectors may be more appropriate economical and just as reliable.

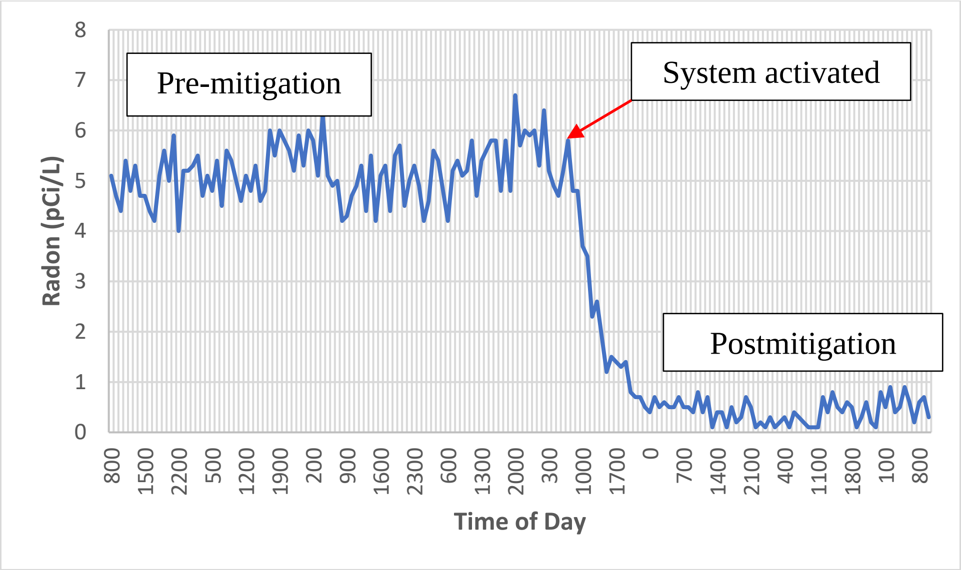


Figure 20. Postmitigation testing using a CRM

Under NAVRAMP possible uses of CRMs would include short-term confirmation testing in which collocated duplicates were both > 4 pCi/L but failed the precision test or in cases where one of the duplicate detectors was lost and the remaining detector was > 4 pCi/L. Another application is to monitor the before/during/after during complicated or difficult radon mitigation. Widespread application of CRMs in a confirmation role is not required since under NAVRAMP validated radon measurements ≥ 4 pCi/L are considered representative of the radon levels during the test period.

In summary, CRM measurements are very useful tools to better understand the measured radon levels within a housing unit or nonresidential building. However, the measurement, although highly accurate, is still a short-term measurement which is only representative of the radon levels present during the period of measurement. If a CRM measurement is significantly lower than the long-term or annual measurement, then there is high probability that the radon levels at other times or seasons are higher than the annual average. Therefore, in cases where the CRM measurement is < 4 pCi/L and the long-term or annual measurement is > 4 pCi/L to reach a defensible testing conclusion, multiple CRM measurements performed in other seasons would be required.

3.4.2 Charcoal Radon Detectors

A charcoal detector consists of an airtight container with a known quantity of activated carbon. To sample radon, the carbon is exposed to the area tested (typically, by removing the lid) for a period of 2 to 7 days. During the exposure period, the radon in the air is absorbed and desorbed by the charcoal granules. At the end of the sampling period, the canister is sealed and returned to the laboratory for radiological analysis.

There are two types of charcoal detectors, activated charcoal adsorption which is analyzed by the reading of the gamma radiation released from the decay of Lead-214 and Bismuth 214 and charcoal liquid scintillation which measures the alpha and beta particles emitted by the radon decay products within a laboratory added liquid scintillant. Because absorption sites within the charcoal granules are not specific, water and certain organic vapors compete with radon. Over time, these active absorption sites become irreversibly saturated with water, preventing further radon absorption. If water saturation occurs, the test must be repeated. To retard moisture infiltration, some charcoal detectors are equipped with a semi-permeable barrier which allows radon to enter and exit while retarding moisture entry. The optimal exposure period for a particular charcoal-based detector is based upon the weight of activated carbon and the presence or absence of the semi-permeable membrane. As a general rule, detectors without semi-permeable membranes can be exposed for 2-3 days and those with for up to 5-7 days.

Because charcoal permits the continual absorption and desorption of radon, this device does not give a true, integrated measurement over the exposure time. This means that the reported result may be significantly biased by either episodic or random events during the last 8 to 12 h of exposure.

Another consideration is that all charcoal-based radon detectors have a maximum exposure limit. When analyzed, the spectrometer measures the radon concentration within the charcoal granules. Because ^{222}Rn (the most common isotope of radon) has a half-life of 3.8 days, it is imperative that the detector be read within 2 weeks of the conclusion of sampling.

3.4.3 Electret Radon Detectors

Electret-based radon detectors consist of two distinct parts: the ion chamber and the electret (Figure 21). The ion chamber is a specially designed holder for the electret, which is made of electrically conducting plastic. This feature permits the uniform discharge of any static energy generated by the decay of radon or radon daughters in the air inside the chamber. An electret consists of an electrically charged wafer of Teflon that has been treated to hold a stable electrostatic potential. This potential attracts oppositely charged ions that collect on the electret surface, thus neutralizing the surface charge and reducing the electrostatic potential. The surface potential is measured before and after exposure, using a specially designed voltage reader. The decrease in surface potential during exposure is proportional to the concentration of radon integrated over time. When new, the voltage of an electret is between 700 and 750 V, and the electret can be reused until the voltage drops below 200 V. The discharge rate, or volts per unit of time per radon concentration, depends on the volume of the ion chamber and on the sensitivity of the electret. High-sensitivity electrets discharge at a rate 11 times that of low-sensitivity electrets. For short-duration tests, such as 90-day tests, a higher discharge rate is needed for better accuracy. For example, a 90-day measurement conducted at 1 pCi/L of radon with a low-sensitivity electret would yield only a 6 V drop, whereas a high-sensitivity electret would yield a 66 V drop. The higher voltage drop results in an accuracy increase of about 50% in this example. Conversely, for longer exposures, such as 240 days, the drop in voltage for the high-sensitivity electret would be 176 V, or 35% of the usable voltage for the electret. The lower-sensitivity electret would drop by only 16 V, losing only 3% of its usable voltage. With respect to processing electrets, both NRPP, NRSB and NAVRAMP require certification for the operator.

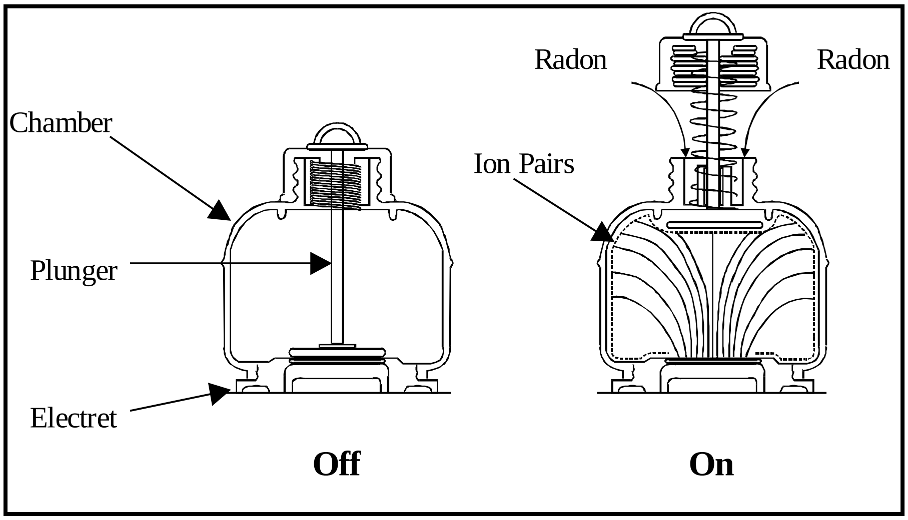


Figure 21. E-Perm® electret-based radon detector with a model S chamber.

As with charcoal, one of the major advantages of electret-based radon measurements is the low cost per measurement. Because electret-based detectors are reusable, electret measurements also can be performed for less than $5 (excluding field labor). Unlike charcoal canisters, electrets can be placed for more than 7 days and are insensitive to water and organic vapors. In addition, electrets are true integrating devices, meaning they are not dependent upon the last 8 to 12 hours of exposure. The total voltage discharge is proportional to the average radon concentration during the exposure period. Most important, electret readers are field portable; that is, detector analysis can be performed at the job location. However, unlike charcoal, an electret does have an upper limit for radon exposure. For new electrets, the maximum usable dose is approximately 250 pCi/L-days (1 pCi/L-day = 1 pCi/L exposure for 1 day). Therefore, each time an electret is used, care must be taken to ensure that sufficient usable voltage remains to perform the measurement.

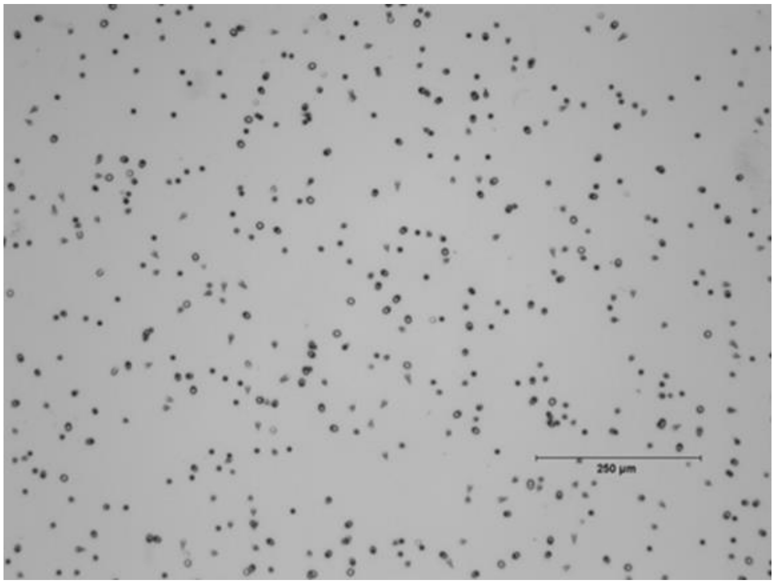
With respect to disadvantages, electrets are sensitive to external gamma radiation, microwaves and other similar types of high-level electromagnetic radiation. In addition, a correction must also be made for altitude. Although the reader is readily transportable to the job site, the detectors must be read within a controlled temperature and humidity environment between 68 and 75°F and 40 to 60% relative humidity (RH). The electret surface can also be easily damaged by touching or impact. Another issue with using electrets is dust and lint. The presence of dust or lint on the Teflon disk can result in significantly higher bias yielding an unacceptably high RPD for the measurement. Prior to having the initial voltage read, the radon chambers and the electret surfaces should be cleaned by dry compressed air. For exposures in known dusty environments the chamber/electret detector will need to be placed in a paper bag or unsealed plastic bag or inside a manufacturer's special purpose bag to minimize the dust exposure. To prevent dust introduction into the chamber upon retrieval, the plunger (S Chamber) and slider (L-00) chamber must be inspected and potentially cleaned prior to the deactivation to prevent dust introduction into the chamber. Although most of the dust/lint issues are a result of field deployment, the use of an air cleaner during detector reading has been shown to be beneficial. Another issue is holding times, unexposed electrets do discharge over time. Depending upon the length of exposure (e.g., 2 days) or 30 days this loss may not be significant (about 3 V per month on average). For example, a 2-day S-ST test read within hours of retrieval was 1.9 pCi/L. However, 30 days later the electret was 3 V lower and calculated as 2.5 pCi/L. For a 30-day test, the voltage loss of 3 V after 30 days does not change the radon results. So, consideration should be taken as to the time lag for processing the electrets. Another return for laboratory analysis concern is the chamber. Although S chambers can be returned for analysis while still inside the chamber, electrets in L chambers must be removed and covered with the storage cap prior to return. Although L-OO chambers in theory can be deactivated with the slider and shipped to the laboratory for analysis, there have been reported issues of excessive electret voltage drops during shipping. It is therefore recommended that the electrets be removed from the L-OO chamber and placed in the storage cap prior to shipping.

3.4.4 Alpha Track Radon Detectors

For long-term measurements (>90 days), using CRMs is generally not considered cost-effective. Instead, either electrets or alpha track detectors (ATDs) are used. ATDs, the oldest and best understood of long-term measurements, work on the principle of counting physical damage (tracks) to an acrylic chip (CR-39) caused by alpha particles generated during the radioactive decay of radon (Picture 1). During the deployment of an ATD, radon diffuses through a filtered membrane (in the most common type of ATD). If radon undergoes radioactive decay while in the holder, the subsequent radon daughters are attracted to the CR-39. If the daughters deposit on the surface of the CR-39, subsequent alpha decay will leave a submicroscopic track on the surface of the CR-39. After the ATD is retrieved, it is returned to the laboratory for development and analysis. This is performed by disassembling the ATD, removing the CR-39 chip from the holder, and placing the CR-39 chip in a heated caustic solution (potassium or sodium hydroxide) for about 12 to 24 h (depending on the vendor). The caustic development or etching enlarges the alpha tracks so that they can be viewed and counted under a microscope. The tracks per unit of area (track density) as a function of time (days) are proportional to the radon concentration (pCi/L). Picture 2 shows typical ATDs by different manufacturers. Table 8 provides a summary comparison of the most common types of passive detectors.

The principal advantages of the ATD are their relatively low per unit cost, availability in large numbers and their compactness. If properly packed for their return shipment to the laboratory holding time is not a significant issue. Since they are not considered hazardous, they can be returned via US Mail or by express air services. An important advantage of the ATD over all other forms of measurement is the fact the chip once developed becomes a permanent exposure record. Therefore, in the event of a contested result, the ATD could be reread by the laboratory.

The principal disadvantage of an ATD is its slow sensitivity necessitating a minimum 90-day exposure. At low concentrations (e.g., < 1 pCi/L), precision errors may occur if only a small area of the chip is read. ATDs also have an upper exposure limit and do have an expiration date. Another issue is package leakage during shipping, storage and handling which can result in an increased background and bias the measurement higher.



Picture 1. Typical tracks (dark spots) on a developed ATD chip

Picture 2. Typical ATD by different manufactures

For over 30 years, ATDs have been limited to exposures of ≥ 90 days. However, within the past 5 years, short-term ATDs (10-to-90-day exposure) have become commercially available.

3.4.5 Electronic Integration Monitors

Electronic integration monitors (EIM) use a solid-state electronic chip to record the alpha particles produced by the decay of Radon-222, Polonium-218, and Polonium-214. Unlike CRMs which report hourly, EIMs provide an integrated result for the entire exposure period. The key advantage of EIM is their relatively low cost when compared to CRMs. Unfortunately, most of the commercially available EIMs have not been accreted by NRSB or NRPP and are not suitable for reportable radon results (only one EIM is listed by NRSB). However, evaluation by the US Navy has found that the detectors are suitable for nonreportable diagnostic measurements of at least 2 weeks in duration.

Table 8. Summary comparison of passive radon detectors

Detector Type	Passive/ active		Typical uncertainty [%]	Typical sampling period
Alpha-track detector (ATD)	Passive		10 – 25	1 – 12 months
Activated charcoal detector (ACD)	Passive		10 – 30	2 – 7 days
Electret ion chamber (EIC)	Passive		8 – 15	5 days – 1 year
Electronic integrating device (EID)	Active		~ 25	2 days – year(s)
Continuous radon monitor (CRM)	Active		~ 10	1 hour – year(s)
	Uncertainty expressed for optimal exposure durations and for exposures 5.4 pCi/L (200 Bq/m ^{3})			
	Source: Table 6, WHO Handbook on Indoor Radon (2007)			

3.4.6 Measurement Of Radon Decay Products

Although measuring radon gas in air is the most common method used today by radon testing companies within the United States, another method measures the radiological activity of radon progeny that have become attached to particles suspended in air. To perform this measurement, the equilibrium ratio (ER) must either be determined or assumed. Simply speaking, the ER is the percentage of radon daughters attached to particles that are suspended in air. The ER is calculated by dividing the total concentration of radon decay products (RDPs) present by the concentration that would exist if the RDPs were in radioactive equilibrium with the radon gas concentration present. Therefore, at equilibrium (i.e., at an ER of 1.0), one working level (WL) of RDPs would be present when the radon concentration was 100 pCi/L. However, because of ventilation and plate-out (the attachment of RDPs to the walls, floors, or objects within the room), the ratio can never be 1.0. Residential studies performed by EPA found typically an average ER of 50% (the range was from 30 to 70%) for typical residential structures with average air recirculation rates.

In most nonresidential buildings, however, the ERs are consistently lower, ranging from 5 to 30% with an average ER of 25%. The exact reasons for the lower average ER are subject to debate. But most nonresidential buildings are nonsmoking, do not have pets, have more efficient heating and air-conditioning filters, and are usually cleaned more frequently. Therefore, for the most part, the common sources for residential particles in air are absent.

To convert from units of WL to equivalent gas concentration in pCi/L, the WL is multiplied by 100 and then divided by the ER (Eq.[1]). For example, 0.02 WL (RDPs) × 100/0.5 (50% ER assumed) would equal an equivalent gas concentration of 4.0 pCi/L. It is important to note that if the ER is assumed, the gas concentration should be identified as "equivalent gas concentration" to avoid confusion. Table 9 shows equivalent gas concentration in picocuries per liter at various WL concentrations and ER at a 4 pCi/L gas concentration.

$$\textbf{Radon (pCi/L)} = \frac{\textbf{WL} \times \textbf{100}}{\textbf{ER}}$$

Equation 3. Conversion from gas to WL

For many years EPA set the action level for measuring RDP at 0.02 WL (EPA May 1993, 402-R-92-003, and EPA November 2006a, 402-K-06-093), which is equivalent to a 4.0 pCi/L gas concentration at an ER of 0.5 (the default value recommended by EPA if the ER is unknown). But in 2007 EPA lowered the action level from 0.02 to 0.016 WL (the gas concentration action level remained unchanged at 4.0 pCi/L) and decreased the assumed ER to 0.4 (EPA May 2007, 402-K-07-009). However, in the most recent *Citizen's Guide,* testing options using RDP were not included (EPA January 2009, 402/K-09/001). Instead, only radon gas measurement options were provided.

The most common WL measurement devices are CRMs or electrets that consist of a pump, filter paper, and detector. The basic principle of operation is that dust particles with the RDPs attached become trapped on the filter paper. The detector then measures the alpha particles emitted by ^{218}Po and ^{214}Po as a function of time and flow rate. Studies have shown that even common occurrences within buildings can change the ER and, in turn, affect the WL measurement. For example, simple routine occurrences such as smoking, lighting a candle, cooking, dusting, or vacuuming have resulted in doubling the response of the WL meter. Conversely, increasing the amount of air movement within a building by turning on a ceiling fan or the heating and air-conditioning blower can reduce the response of the WL meter by up to 1 order of magnitude.

Table 9. Equivalent gas concentrations at 4 pCi/L for various equilibrium ratios

Equilibrium ratio	Working level	Equivalent gas concentration (EpCi/L)
0.05	0.002	0.4
0.1	0.004	0.8
0.2	0.008	1.6
0.3	0.012	2.4
0.4	0.016	3.2
0.5	0.02	4.0
0.6	0.024	4.8
0.7	0.028	5.6

The generally accepted theory for why routine activities such as cooking or vacuuming affect the measurement is that they generate additional airborne particles, increasing the number of sites suitable for RDP attachment and their subsequent capture on the instrument's filter paper. This results in an increase in measured WL. The reasons why a ceiling fan or heating system blower cause a decrease in instrument response are not as clear. As a result, two divergent but viable theories have been proposed. In the first theory, it is assumed that the RDPs, once adhered to an airborne particle, become irreversibly attached. As these particles (including the attached RDP) collide with a fixed object in the room, they become "stuck" and are removed from the breathing zone. For RDPs that are not attached to particles, the increase in air velocity increases the probability that they will also collide with a fixed object in the room and become irreversibly attached. However, the second theory assumes that some of the RDPs are not irreversibly attached to airborne particles. Increasing the air velocity in the room also increases the frequency and the energy of collisions between air molecules and attached RDPs. As a result, some of the attached RDPs are dislodged and become unattached once again. Because these unattached RDPs (more accurately visualized as molecules) are small enough to pass through the filter paper on the WL meter and not become trapped, the instrument would not be able to measure the emitted alpha particles.

The importance of what exactly is happening with the unattached RDPs is not academic. It has a direct bearing on the dose and hence the risk of contracting lung cancer. It is generally acknowledged that the respiratory system filters out a significant number of RDPs attached to large particles in the nose and throat. The greater risk comes from the RDPs attached to smaller particles that manage to get past the body's natural defenses and penetrate deeper into the lung. In addition, it is well known and accepted that unattached RDPs have a 20–30 times greater efficiency in delivering a dose to lung tissue. Therefore, any increase in unattached RDP concentration, no matter how small, in the breathing zone would significantly increase the dose to lung tissue.

Because of the higher risk associated with ERs >50% (an ER of 3 pCi/L at 0.65 is equivalent in risk to 4 pCi/L), EPA rationalized that WL measurements should continue to be listed as a viable testing method. However, these measurement uncertainties (when the ER is unknown or highly variable) and the difficulty in interpreting the data were the primary reasons that WL measurements generally fell out of favor with the radon testing industry.

In summary, answering the question which is better, measuring radon gas or radon daughter (WL) concentrations is not easy or straight forward. Although it has long been accepted that the radon daughters, not the radon gas, is responsible for the dose to the lung, there is a possibility of significant lung dose from unattached fraction which is not reflected in a working level measurement. Radon gas measurements on the other hand are less dependent than working levels on how a building is being used, velocity of the indoor air, and occupancy. Consequently, radon gas measurements may give a better estimate as to the potential hazard, not the current one. Another consideration is calibration. Whereas radon gas calibration is readily available from several established radon calibration chambers; similar calibration facilities for working levels are not. Finally, is the simple fact that if the radon gas levels are low, so is the risk. Because of all these considerations, working level measurements are not allowed under NAVRAMP, only detectors and monitors which measure gas directly are permitted.

3.5 TESTING FOR RADON IN WATER

Most naval installations obtain their drinking water from processed and treated supplies. This processing and treatment of the water removes most if not all the dissolved radon (if present). The sources of these water supplies are checked on a regular regulatory basis to ensure that the water is safe to drink. Included in these tests are gross radiological assessment which the total radiation from all sources not just radon. For this reason, NAVRAMP does not require routine radon in water tests. It is also important to note that to date, no indoor radon issue caused by elevated radon in water issues has been identified within the Navy or USMC.

Although the action level for radon in water can vary from local health department to department, a conservative number for planning purposes is ≥ 4,000 pCi/L. However, this limit is based not upon increased risk of lung cancer but an increased risk of stomach cancer. It is also important to note that on average it takes 10,000 pCi/L in water to provide 1 pCi/L in air.

EPA has recommended two methods for routine measurement of radon in water. The emanation method, in which radon is degassed from the water and transferred into a Lucas scintillation cell, has a detection limit of approximately 0.05 Bq/L (1 pCi = 0.037 Bq) for a sample volume of 100 mL (Crawford 1989). In the liquid scintillation method, the water is injected directly into a scintillation solution and counted in an automated liquid scintillation device; this method has a detection limit of about 0.4 Bq/L using a sample volume of 10 mL (Prichard and Gesell 1977) and EPA Method 913 (EPA June 1991, Report EMSL/LV). All methods require careful sampling because of the rapid loss of radon from the water when it is agitated and open to the atmosphere. The EPA [EPA 1991, *Fed. Regist.* **56**(138): 33050] estimated a practical quantization limit for radon in water (based on the ability of laboratories to measure radon within reasonable limits of precision and accuracy) at about 10 or 11 Bq/L (1 pCi/L = 37 Bq/m^3).

With respect to current radon in water testing standards (*Protocols for the Collection, Transfer and Measurement of Radon in Water*, ANSI/AARST MW-RN 2020) provides updated methods and procedures for sample collection and specific requirements for the radon in water laboratory to meet. NAVRAMP accepts this standard without exception.

4. OVERVIEW OF RADON MITIGATION

4.1 CONSIDERATIONS IN MITIGATION SELECTION

If passive mitigation techniques are not viable, then the installation of an active mitigation system will be needed. Although initial installation costs and long-term operation and maintenance costs are important considerations, the following issues may have an impact on the selection and system design.

- added energy for conditioning outdoor air
- aesthetics
- noise reduction
- minimal loss of living or working space
- local and state requirements
- proposed and pending renovations
- an understanding of the occupants' concerns about radon exposure

If all active mitigation systems were equivalent in installation and O&M costs, the decisions would be greatly simplified. But the three most common types of mitigation (SP, ERV, and SSD) differ significantly in installation and O&M costs. For example, using a simple intake grill and duct system, a Type 1 SP mitigation system costs approximately $500 to install. However, the annual operation cost (e.g., energy costs associated with conditioning the air) and the maintenance costs (e.g., cleaning filters and rebalancing the system) are significantly higher than for ERV and SSD. Because O&M of a building's radon mitigation system is permanent for the remaining life cycle of the building, the true cost of mitigation must be looked at over a much longer period. Figure 22 compares the 10-year life-cycle energy consumption cost and the initial installation cost for each of the mitigation systems. For SP and ERV, the higher operation costs reflect the added heating and cooling load for the intake of outside air and maintenance. Because of cost considerations like these, whenever feasible, SSD should be preferred over ERV and SP.

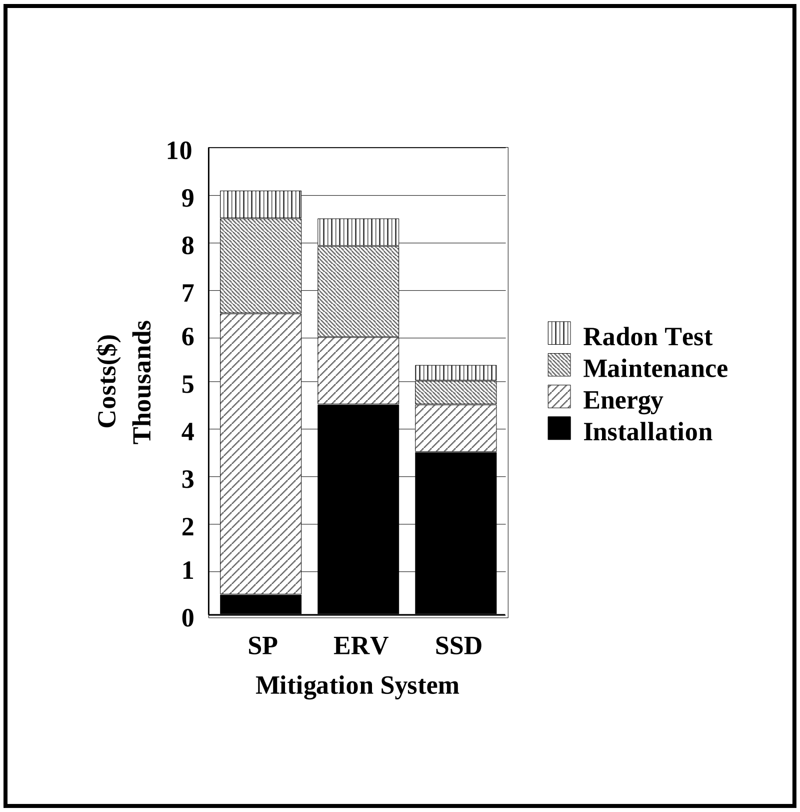


Figure 22. Comparative 10-year cost for radon mitigation.

4.2 RADON MITIGATION STANDARDS

It is important to note that in 2012, EPA initiated a voluntary consensus-based standards initiative with the radon industry (https://www.epa.gov/radon/radon-standards-practice). The subsequent standards produced by this partnership have superseded and consequently replaced the previous EPA standards and guidance documents. Consequently, for this version of the guidebook a comprehensive review was performed and where applicable, changes were made to the NAVRAMP mitigation specifications. Therefore, for mitigation standards references to be utilized in a statement of work, requests for proposal, performance work statements and similar types of documents use this document, *Navy Radon Assessment and Mitigation Program Guidebook for Naval Shore Installations* (DATE) and as applicable the standards listed below. These standards can be viewed or purchased on-line at https://standards.aarst.org/ .

- *Radon Mitigation Standards for Schools and Large Buildings*, ANSI/AARST RMS-LB-2021
- *Radon Mitigation Standards for Multifamily Buildings*, ANSI/AARST RMS-MF-2021
- *Standard Practice for Installing Radon Mitigation Systems in Existing Low-Rise Residential Buildings*, ASTM E2121-13 (ASTM 2013)

- *Radon Mitigation,* UFGS-31-21-13 (UFGS 2018)

4.3 TYPES OF RADON MITIGATION SYSTEMS

Generally speaking, radon mitigation is divided into two basic categories passive and active. Passive mitigation uses nonmechanical measures to control radon entry into the living or occupied space. Typically, this involves the sealing of cracks and slab penetrations or other subslab openings into the living or occupied space. Another method used in new construction entails the installation of a passive stack vent pipe during construction (Section 7.1) which allows radon soil gas to bypass the living or occupied areas and flow directly to the outdoors. Another example of a passive technique is to increase the natural ventilation rate within a crawlspace or other nonconditioned space. The other category, active mitigation, entails using mechanical means, such as a fan or blower, to either dilute or control the entry of radon into the living area. Pre-entry mitigation is a technique that retards radon entry into the living area. Common examples of this type are shell pressurization (SP) and subslab depressurization (SSD), and submembrane depressurization (SMD) within crawlspaces. Post-entry mitigation involves the treatment of the radon-laden air inside the room or building. Examples are energy recovery ventilation (ERV), supplemental air mitigation (SAM), increased outdoor make-up air via the existing heating, ventilation and air-conditioning (HVAC), dedicated outdoor air system (DOAS) and high-efficiency particulate air (HEPA) filtration (currently not supported by EPA and is not a NAVRAMP approved mitigation method).

Because of the diversity in style and construction of naval installation buildings, a single mitigation approach for all buildings at an installation is highly unlikely. In addition, in some buildings, a combination of mitigation methods may be required for effective radon reduction. Therefore, building-specific mitigation diagnostics (measurements that assist in the selection of a mitigation system) should be conducted to ensure that a proper mitigation system selection is made. Mitigation method selection criteria always include costs (installation and O&M), probability of success, and direct impact on the building occupants. Other considerations might be:

- Energy consumption
- Security and safety concerns
- Aesthetics
- Noise generation
- Loss of indoor functional space
- Proposed and pending renovations
- Possible impact of mitigation system installation on mission
- Projected remaining lifetime of the building
- Understanding of the occupants’ concerns
- Life-cycle cost

As a general rule, because of their long-term cost-effectiveness, passive, SSD, and SAM (nonresidential only) methods should always be considered first. If these methods are not viable, then other mitigation methods (e.g., ERV, SP) should be considered. Under no circumstances should HEPA systems or other methods that alter the radon decay product equilibrium be used, because their efficacy in reducing risk is uncertain.

Upon completion of a mitigation system installation, postmitigation radon testing shall be performed by the mitigation contractor to ensure that radon levels are <4 pCi/L. All postmitigation testing shall be short term and in accordance with NAVRAMP testing policies, guidelines, and procedures. Postmitigation testing shall be performed no sooner than 24 h and no later than 30 days after system activation or, in the case of passive mitigation, completion. Within 30 days of the reporting of the postmitigation test results and at the discretion of the installation, an independent postmitigation test may be performed to verify that radon mitigation has indeed occurred. The extent and frequency of this verification postmitigation testing are at the sole discretion of the installation.

Typically, installation costs for a passive system are less than half those of an active system, and a passive system has no operation and maintenance (O&M) costs (i.e., energy for operation). Unfortunately, successful passive mitigation has proved difficult because all radon entry pathways within the room or building must be identified and negated. However, noted success has been observed in buildings with drainage sumps, French and perimeter drains, and major openings exposed to soil (e.g., wall pipe penetrations and beam pockets). For buildings in which these significant soil gas conduits (not to be confused with electrical conduits) are not present, the effectiveness of passive mitigation measures is greatly reduced. Another form of passive mitigation is the restoration of a building's existing mechanical systems (HVAC) and exhaust to the original design specifications. This would include rebalancing the building's conditioned air supply, return air, fresh-air and exhaust air volumes.

Because the available skill sets vary widely from installation to installation, a determination will need to be made as to how much, if any, of the mitigation work will need to be contracted vs. being performed in-house. If contracting the mitigation work is required, then NAVRAMP requires that the mitigation contractors meet very specific requirements (NAVRAMP Guidebook Section 4.2.9).

This chapter contains references, trade names, trademarks, and manufacturers for specific commercial products. These references do not necessarily constitute an endorsement or recommendation by the United States Government or any agency thereof.

4.3.1 Shell Pressurization Mitigation

SP, the oldest radon mitigation method, retards radon entry by mechanically introducing sufficient outdoor air to the building to induce a positive pressure (typically ≥4 Pa) across the slab and into the soil (Figure 23). The two basic designs (with minor variations) are

- Type 1 SP: Uses the building’s existing mechanical system to condition the required volume of outdoor air (Figure 23).
- Type 2 SP: Uses an independent mechanical system to condition the outdoor air before its discharge into the structure (Figure 24-25).

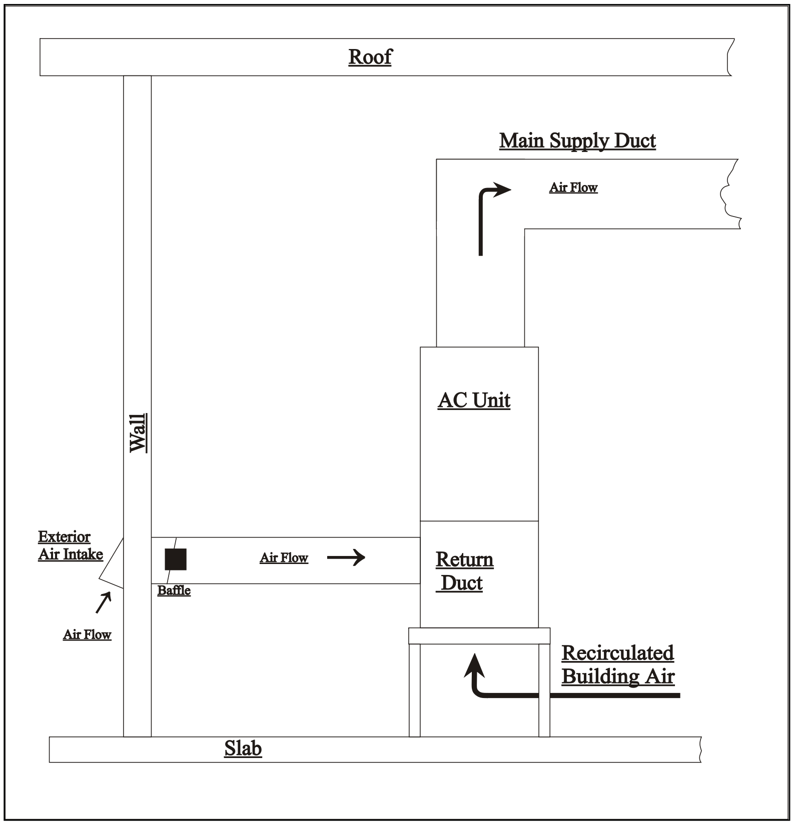


Figure 23. Example of aType 1 SP system.

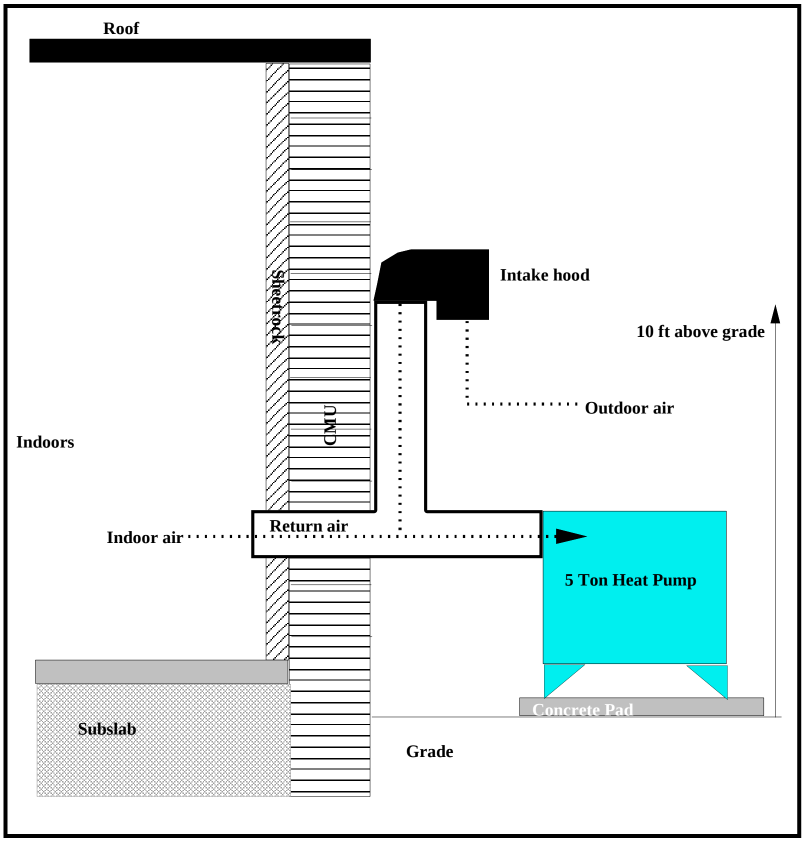


Figure 24. Example of a Type 2 SP system.

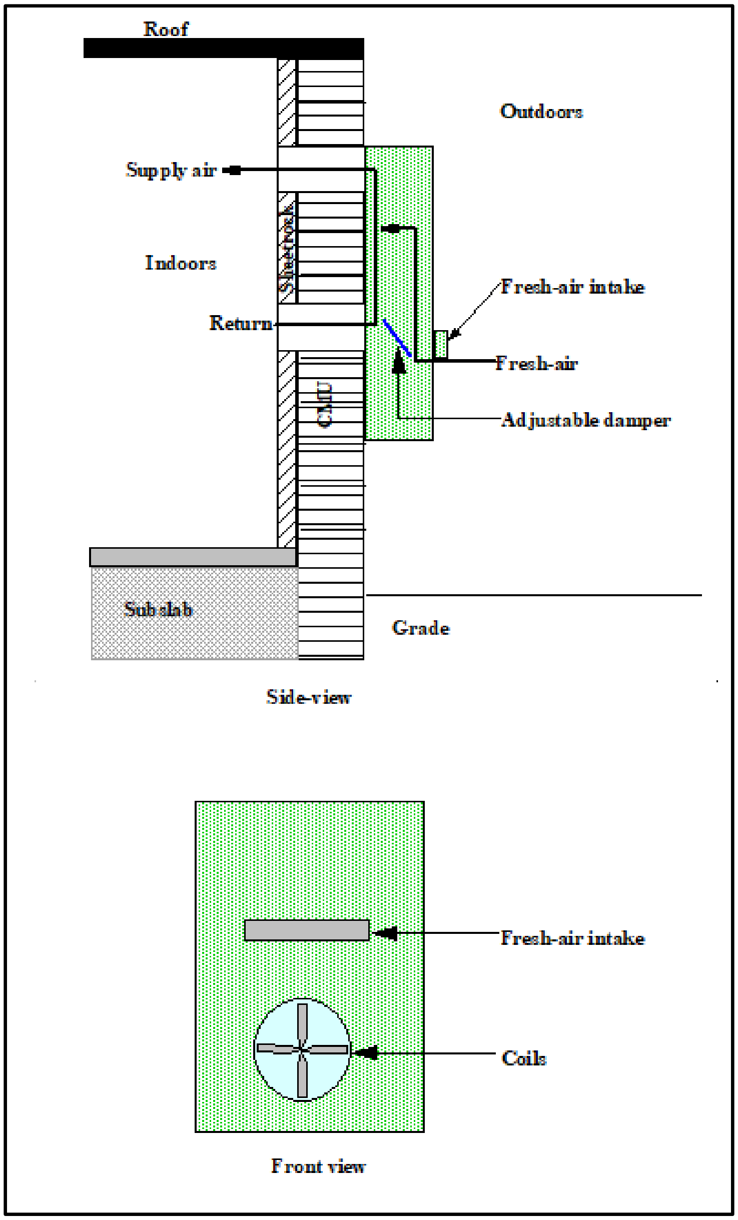


Figure 25. Example of wall-mounted Type 2 SP system.

The deciding factor for the selection of a Type 1 or Type 2 SP system is the ability of the existing mechanical system to condition the added volume of outdoor air. Although this information is readily available on the as-built design drawings or the unit itself, with older equipment (e.g., ≥5 years old) performance degradation may be an issue that needs investigation before Type 1 SP mitigation is attempted. If the HVAC unit has sufficient capacity to condition the additional outdoor volume, the existing fresh-air duct (from the exterior intake to the return air box) is replaced with a larger duct and a higher-capacity damper. A popular cost savings option in this case is the addition of an inline blower fan to the existing air intake duct in lieu of replacement. For buildings without existing intake air ductwork, an appropriately sized duct is run from the exterior to the return box of the unit.

For Type 2 SP mitigation, there are many varieties of commercially available units which can condition the required outdoor air volume. Selection of the most appropriate unit is based mainly on the volume of outdoor air and the year-round climate conditions. Common examples are

- single-pass HVAC or heating/air-conditioning units that bring in 100% fresh air (i.e., there is no return air)
- desiccant makeup air units
- split units with a dedicated air makeup
- specially modified heating/air-conditioning units

Although a highly effective radon mitigation technique, SP is extremely vulnerable to occupant interaction. The technique works only as long as the building is under positive pressure. Therefore, all windows must be kept closed year around and doors opened only for normal entrances and exits. In addition, all the pre-filters (bug screens) and system filters must be cleaned or replaced frequently (e.g., weekly or monthly) to ensure that the required volume of fresh air is being supplied. The energy penalty (e.g., the energy cost to condition the outdoor air before it is discharged into the building) is also quite high. For all these reasons, SP mitigation is generally considered the last mitigation alternative.

Design specifications for SP mitigation systems are building- and application-specific—the design for one building will not be readily interchangeable with another. Many considerations go into the design of an SP system to ensure that the current mechanical system(s) can handle the added conditioning load and that the possible increase in humidity would not place the building within the range for inducing mold growth (≥60% RH). Therefore, if SP is selected as the mitigation method, the design will need to be reviewed and approved by a qualified mechanical engineer before the mitigation system is installed. Typical design features for an SP system would include but would not be limited to the following:

1. Sufficient conditioned outdoor air volume to pressurize the building envelope to between (+) 4 and 8 Pa relative to the outdoors.
2. Intake air filters with a minimum efficiency reporting value (MERV) rating of 8 or greater (ASHRAE 2007, 52.2-2007).
3. To the best extent possible, the system meets fresh-air intake requirements of *DoD Minimum Antiterrorism Standards for Buildings* (UFC October 2003, UFC 4-010-01, updated 10 October 2013).

4.3.2 Subslab Depressurization Mitigation

For buildings with slabs or basements, SSD is the most common means of radon control within the United States. This method uses a pipe inserted through the slab and a fan connected to the pipe (Figure 26). When the fan is activated, the area beneath the slab (subslab) is depressurized. The resulting depressurization prevents radon entry into the living area by redirecting the subslab radon into the pipe for discharge into the atmosphere, where it is harmlessly diluted. However, the overall effectiveness of SSD is limited by pre-existing conditions under the slab that can impede the extension of the vacuum field (e.g., compacted fill, presence of grade beams, enclosed utility vaults, and interior foundations are common conditions that reduce the vacuum field extension). Slab size is another consideration. Under ideal conditions (e.g., noncompacted fill, no grade beams or other structures impeding vacuum) a single SSD system with a 4 in. vent duct (the most common size) can typically depressurize between 2,000 and 5,000 ft^2 of subslab. Systems with vent ducts larger than 4 in. can depressurize up to 10,000 ft^2; however, they typically cost more to install than multiple 4 in. duct systems. Therefore, in larger buildings, the use of two or more independent systems is not uncommon.

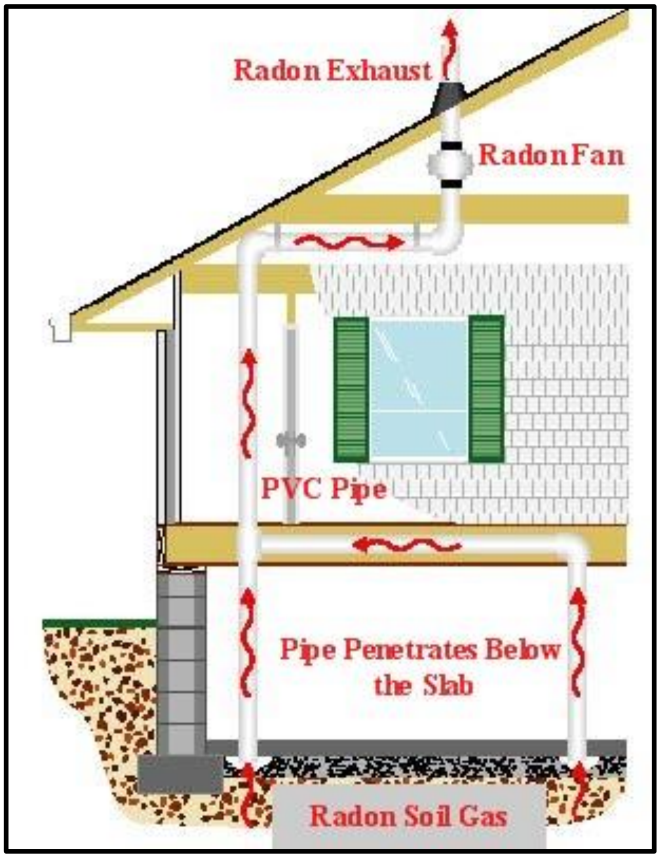


Figure 26. Example of an SSD system in a house with a basement.

Within the US Navy and US Marine Corps SSD mitigation represents about 95 % of all installed mitigation systems worldwide. Long-term studies of this method (+30 years) have found it to be the most durable, reliable and over time the least expensive to operate and maintain. In fact, SSD systems installed in family housing in the early 1990s are still maintaining radon levels < 4 pCi/L.

Compared with other active mitigation methods, SSD has the most economical lifetime ownership costs (Figure 22). If a system is properly installed, maintenance is typically limited to the infrequent replacement of the fan and performance indicators (a fan typically lasts 10 years, a performance indicator 5 years). All other SSD components (e.g., pipe, fasteners, pipe straps), if properly selected and installed, will last for the remaining lifetime of the building.

The three basic designs (with minor variations) are

1. Type 1 SSD: an externally mounted pipe/fan system with an exterior penetration (Figure 27)
2. Type 2 SSD: an externally mounted pipe/fan system with an internal penetration (Figure 28)
3. Type 3 SSD: an interior pipe penetration with a roof- or attic-mounted fan (Figures 29 and 30)

Another consideration in selecting an SSD design is planning for future O&M of the radon system. Although SSD systems do not require any specific routine maintenance, some system components will need to be replaced eventually because of failure or as part of a preventive maintenance schedule. In addition, to verify that the system is working, EPA recommends periodic checks of the system performance indicator in addition to inspecting the system every 2 years. Although the time required for these checks and repairs is minimal (typically just a few minutes), gaining access to the interior of the building can be a time-consuming process. For example, studies conducted by ORNL within Department of Defense nonresidential buildings have found that one-third to one-half of the time expended for Type 3 SSD repairs and inspections was used arranging for access. Conversely, minimal interaction was required for Type 1 and 2 SSD systems. Another consideration is nonresidential roofing. Commercial buildings usually have complex roofing systems that are warranted or bonded by the contactor for a fixed number of years. Installing a pipe through this roof without the support or permission of the contractor would void the warranty for not only the area where the penetration occurred but also potentially the entire roof.

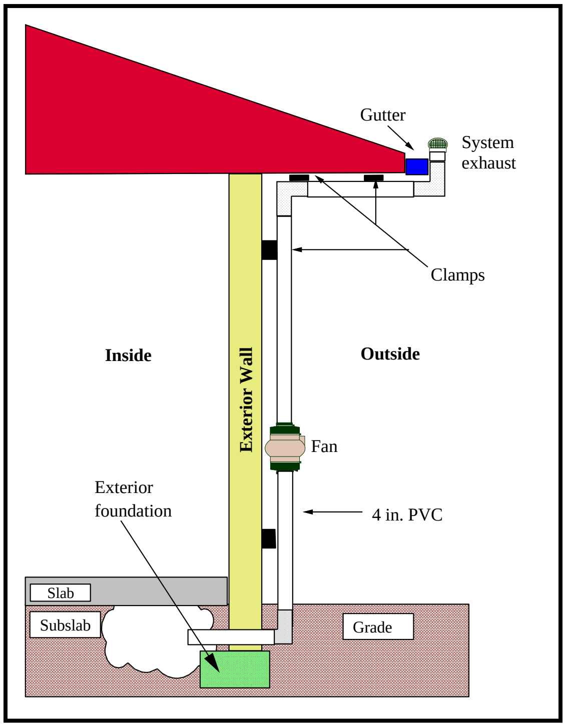


Figure 27. Type 1 SSD system.

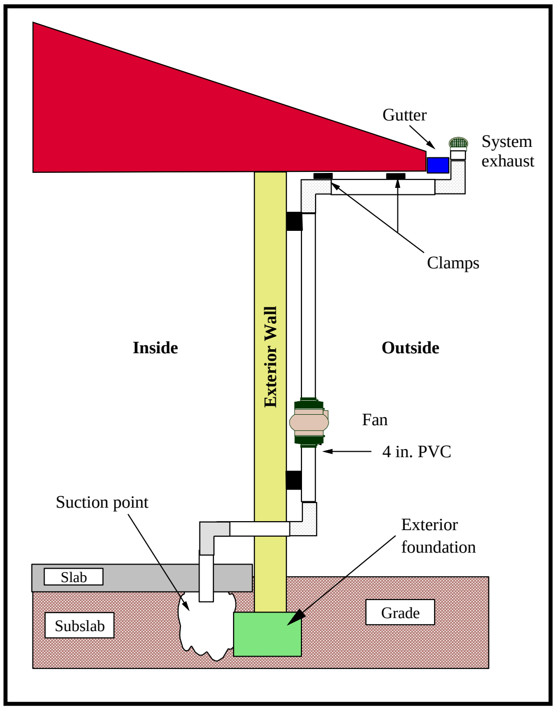


Figure 28. Type 2 SSD system.

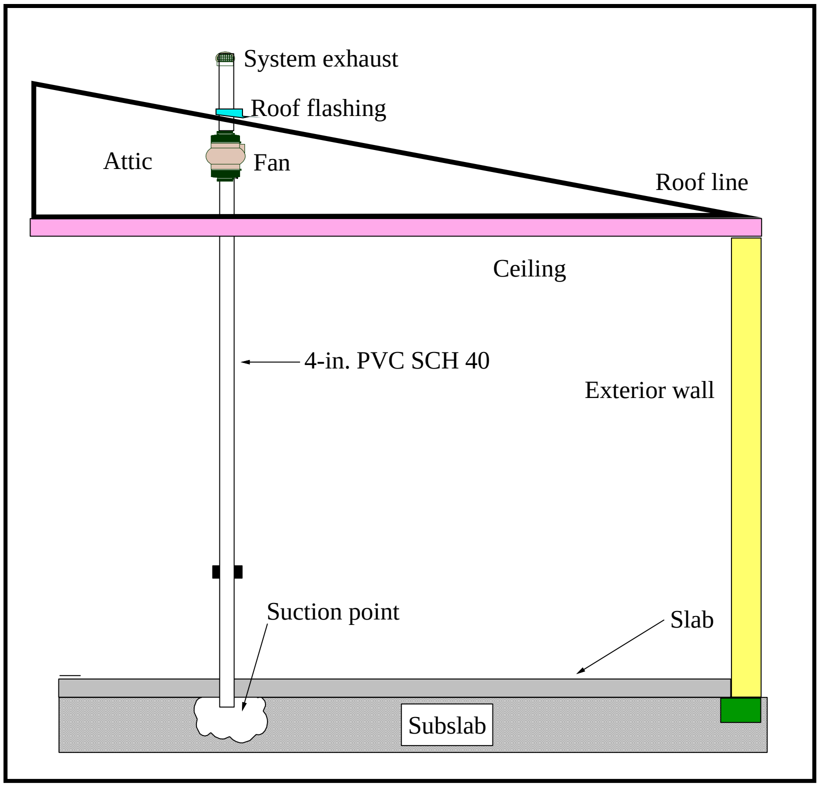


Figure 29. Type 3 SSD system with and attic mounted fan.

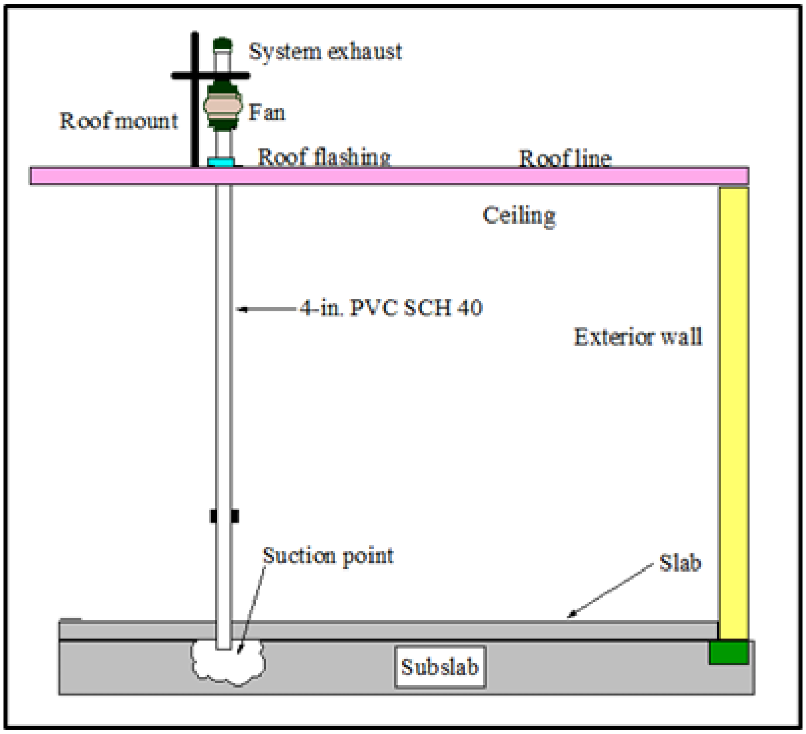


Figure 30. Type 3 SSD system with a roof-mounted fan.

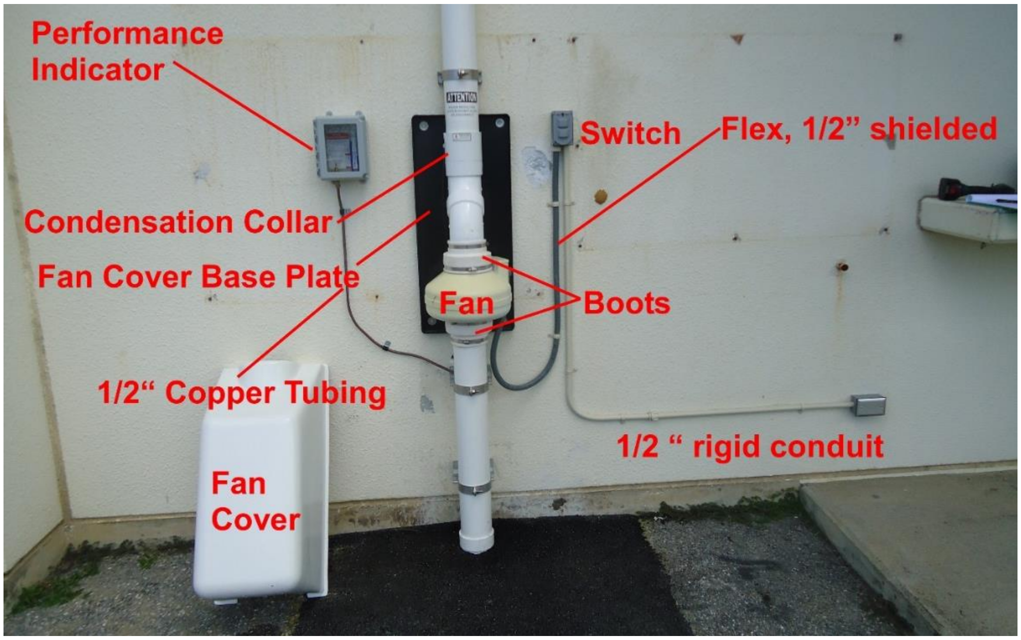
As required by the current mitigation standards (Section 4.2) and NAVRAMP, all SSD systems must have a performance indicator. The indicator must be simple to read or interpret and be located where they are easily seen or heard by building occupants and protected from damage or destruction. The simplest and most common performance indicator, the manometer, deflects a volume of oil in a U-tube or a magnehelic gauge. Others rely on an electrical pressure sensor to trigger either a warning light or audible alarm. Although the current standards require an audible failure alarm, studies by the Navy have found that the alarms are not as effective as routine system inspection for the simple fact that occupants or residents most of the time silence the alarm and do not call for system repair.

4.3.2.1 BASIC COMPONENTS OF AN SSD SYSTEM

A typical SSD mitigation system (Pictures 3 and 4) consists of two main components, the fan assembly (Picture 5) and the vent pipe assembly. The fan assembly includes the fan, rubber boots, performance indicator, all electrical components, and optional components such as a fan cover and/or condensation bypass (Picture 5). The pipe assembly not only includes the pipe and assorted fittings but also the fasteners, channel, pipe clamp and roof cap (Picture 6).

Picture 3. Typical single-story SSD installation.

Picture 4. Typical two-story SSD installation.



Picture 5. Typical fan assembly for an SSD mitigation system.

With respect to the optional equipment, a condensation bypass (its cost is <1/15 that of a typical mitigation fan) is highly recommended for all installations with seasonal patterns and/or periods of heavy rains. Studies have shown that water from condensate and rain passing through the fan greatly reduces the fan lifetime. Limited studies within the Navy have found that on average the condensation bypass adds about 2 years to the fan life expectancy. Fan covers are generally thought of as a cosmetic addition to the system. But studies within the Navy have found that they also have the added benefit of offering some protection to the fan from projectiles (e.g., baseballs, beverage containers, wind-driven debris). In addition, the cover protects the fan from photodegradation of the fan housing, which over time would cause the fan housing to become brittle and crack. Since the covers cost about 2/3 as much as a typical mitigation fan, the cost recovery of installing a cover is not as readily apparent as with the condensation bypass. However, the best estimate is that the cover will add at least 1 extra year to the lifecycle of a typical fan.

Picture 6. Typical pipe assembly for an SSD mitigation system.

4.3.2.2 SSD DESIGN RECOMMENDATIONS

A key consideration often overlooked during SSD design is access to the fan. In the private sector, attic-mounted Type 3 SSD systems are the most common (Figure 31); however, access to such fans for maintenance is typically not a problem in privately owned buildings since the owner is paying for it. Also, monitoring one SSD system is a lot less troublesome than monitoring hundreds of systems. For this reason, it is recommended that, whenever possible, a Type 1 or Type 2 SSD mitigation system be installed. In addition, it is recommended that the fan be installed between 30 to 48 in. above grade to avoid the need of a ladder to access the fan (Figure 32, Picture 5). The performance indicator (Section 4.3.2.11) should be at or near eye level to facilitate routine inspection and should be near the fan.

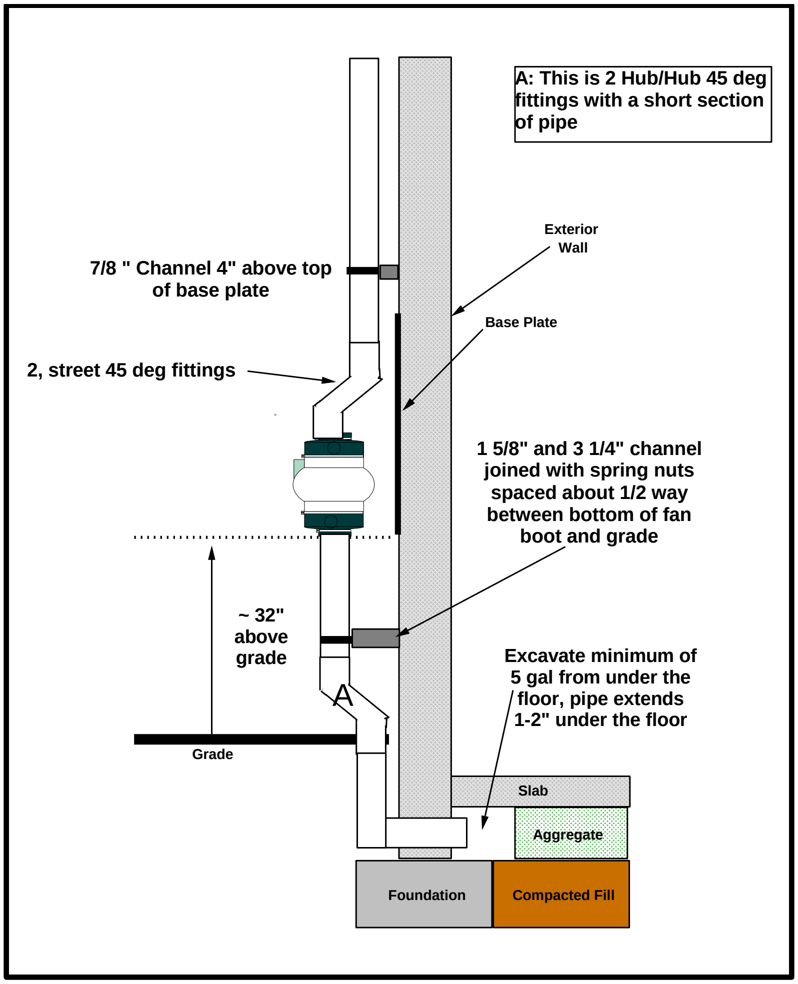


Figure 31. Side view of typical SSD fan assembly.

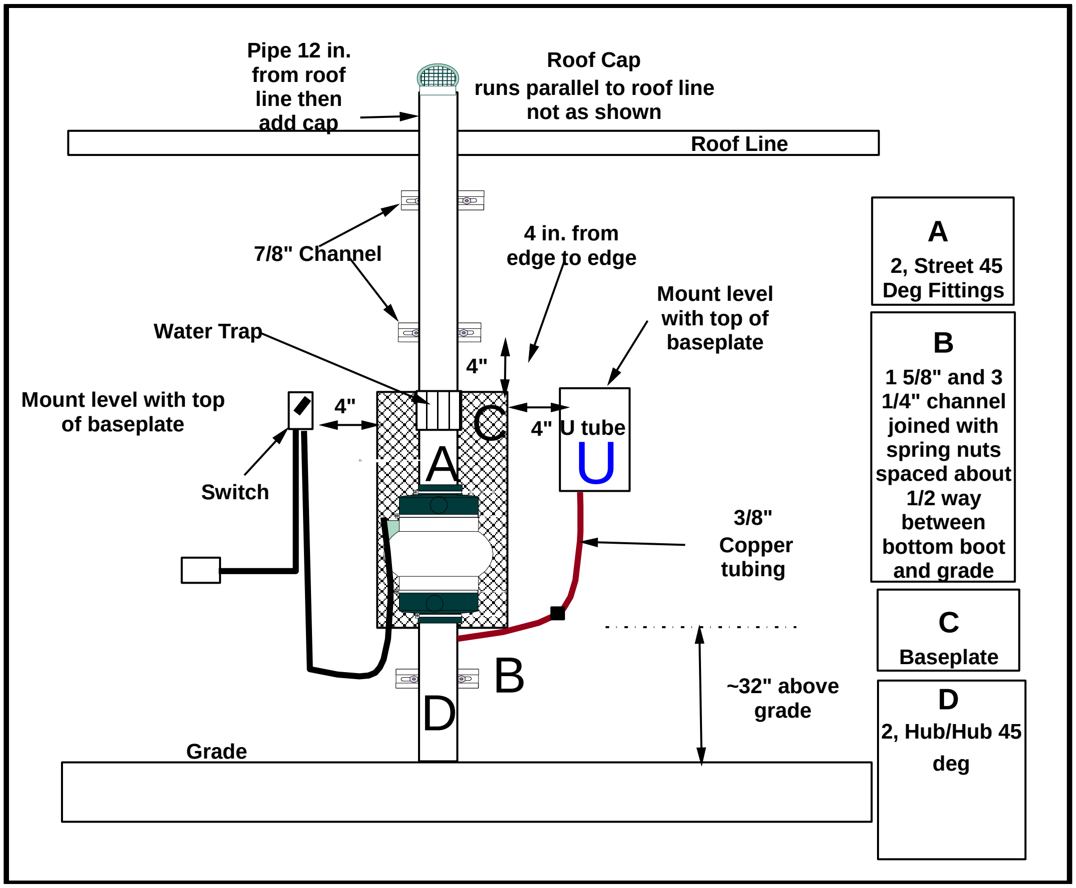


Figure 32. Front view of typical SSD fan assembly.

4.3.2.3 SSD VENT PIPING

Over the years, a variety of materials have been used for SSD vent piping in the Navy and USMC. With respect to pipe schedule, (the higher the number, the thicker the wall), studies of Schedule 20 pipe have found it too thin for most outdoor applications. Studies at one location regularly found breakage at grade (where the pipe comes out of the ground) caused by mowing and trimming activities. Another installation had issues with vandalism—hitting the pipe was sufficient to cause breakage. Thus far, no problems of a similar nature have been observed with SSD mitigation systems with either Schedule 40 or 80 pipe. Therefore, it is recommended that Schedule 20 pipe not be used for SSD vent piping applications unless it is enclosed inside a wall (e.g., in RRNC). Schedule 40 or 80 pipe will perform the venting task equally well; however, Schedule 80 is more expensive. Therefore, it is recommended that all vent piping be Schedule 40.

Vent piping made of polyvinyl chloride (PVC, see ASTM D2665-14) has held up extremely well with no signs of photodegradation, visible cracks, crazing (a network of surface cracks), or creep (a deformation of the pipe caused by stresses). PVC Schedule 40 piping comes in two varieties, solid and foam core. Within the plumbing industry, solid PVC is used for pressurized systems and foam core is used for drainage. Because the radon vent pipe is under pressure (vacuum under the fan and positive above the fan) it would seem that only solid PVC piping should be used. However, long-term studies of foam core vs. solid PVC at the same installation found no difference in durability. Therefore, the deciding factor as to which to choose should be based upon availably and cost.

A similar study of vent piping made of acrylonitrile-butadiene-styrene (ABS) has found cracking, crazing, and creep within as little as 5 years. The biggest problem with ABS is that it is prone to photodegradation, which weakens the wall and leads to cracking and brittleness. Another issue identified was localized creep around pipe strapping with heave crazing. Over time, the crazing led to open cracks that required replacing the entire pipe. Another problem with creep was found in cases where the full weight of the vent piping resided on the lowest ABS fittings. This caused significant deformation of the fitting, resulting in leaks and, in a few cases, catastrophic failure in which the pipe came off the building. With all of these stated problems, the simple solution would be to ban ABS vent piping. However, an important consideration is that PVC piping is not commercially available at all naval installations worldwide. Therefore, at installations where PVC is not available, the following recommendations are made if ABS vent piping is the only choice:

1. The pipe should be painted shortly after installation.
2. Pipe strapping should be at least every 6 ft. on vertical runs and every 4 ft. on horizontal runs.
3. Precautions must be taken to ensure that no weight is applied to any fittings.

Another issue identified was the use ABS fittings on PVC pipe or PVC fitting on ABS pipe. Inspections have found that, over time, these connections can pull apart or in some cases cause failure within the ABS fittings or pipe. The problem is that the degree of thermal expansion of PVC and ABS is a little different. At most naval installations, it is not unusual to find a 20–30°F change within a 24-hour period. During this time, the different plastics expand or contract at different rates. Since PVC is the more robust of the two materials, the ABS component will take the brunt of the stress. This eventually leads to creeping in the ABS component, followed by cracks. Therefore, under NAVRAMP, mixing of PVC and ABS fittings and piping is not allowed.

4.3.2.4 SSD Radon Vent Piping Size Considerations

Within the Navy and USMC, SSD mitigation pipe diameters have varied from 3 to 8 in., depending upon the air exhaust volumes. By far the most common pipe size for SSD mitigation systems has been 4 in., with only a handful of SSD systems requiring larger vent pipe.

One problem that has been observed is within a compacted, wet clay subbase. In some cases, SSD mitigation systems will remove the moisture from under the floor. This drying causes the clay over time to become more permeable and move more air. As a result, the increase in air flow and loss of suction has resulted in SSD mitigation failure in a few cases. A simple replacement of the low-flow/high-suction fan with an appropriate high-flow/low-suction fan restored radon mitigation. However, this was only possible because the installed vent piping was 4 in. pipe. If 3 in. vent pipe had been installed, the smaller diameter pipe (a 4 in. pipe has 80% more capacity) would have caused resistance; and restoration of mitigation would have been unlikely without upsizing the pipe to 4 in. It is therefore recommended that 4 in. pipe be used in all cases in which the subbase consists of compacted, wet clay. It is important to note that this significant permeability change has not been observed in subbases consisting of compacted stone, coral, or sand.

4.3.2.5 Vent Pipe Roof Caps

At the vent pipe termination, three choices exist. One choice is to simply leave it open. However, open pipes are prone to the inadvertent entry of squirrels, birds, and other small animals with consequences that are bad for the animal and the radon fan as well. To prevent entry of small animals, a vertical discharge cap (Picture 7) can be used. On the top of the cap is a course wire mesh that allows for the radon exhaust to escape but prevents the entry of small animals. But this cap does not prevent rain from entering the pipe and ultimately the radon fan. Although radon fans are designed to handle the passage of some water from condensation or rain, they are not designed to handle the multiple inches of rainwater that a tropical storm, typhoon, or hurricane can deliver. In these areas, a lateral discharge cap (Picture 8) is potentially better suited. These caps not only deflect most of the heavy rain but also have mesh to prevent animal entry into the pipe. The downside of these caps is that the discharge is horizontal, not vertical, so the chance of radon re-entrainment is greater if the exhaust is not located properly. In addition, these types of caps in high–air exhaust systems reduce the exhaust flow by about 5–10%. Based upon these findings, under NAVRAMP, all SSD systems must have a vertical or lateral discharge cap, with the selection left up to the installation.

Picture 7. Example of a vertical discharge cap.

Picture 8. Example of a lateral discharge cap.

4.3.2.6 Vent Piping and Fire Codes

An inspection of RRNC vent piping has turned up possible fire code violations at some installations. In most cities, local fire codes prohibit the use of plastic pipe in air plenums and emergency exit stairwells. In these cases, solid metal pipe (not sheet metal duct or dryer vent duct) or fire barrier plenum wrap consistent with the local fire codes should be used.

For Type 3 SSD systems (Figure 29) in which occupied upper floors are penetrated, a determination needs to be made as to whether the ceiling/floor penetration is a rated fire barrier. If is determined to be a fire barrier, then fire rings shall be installed as required by the local fire code.

4.3.2.7 SSD System Vent Pipe Exhaust Location

Currently all mitigation standards (Section 4.2) in the United States require that the radon vent pipe exhaust shall at least be

- 1 ft. or more above the eve of the roof
- 10 ft. or more above ground level
- 10 ft. or more from any window, door, or other opening into the conditioned spaces of the building that is at least 2 ft. below the exhaust point
- 10 ft. or more from any opening into an adjacent building

However, because the mitigation standard in Canada allows for at-grade exhaust, considerable debate has erupted in the United States regarding the need in all circumstances to vent above the eave. The problem with not venting above the eave is possible re-entrainment of radon into the building and possible exposure of people at ground level to the radon exhaust (on average radon exhaust is 200–500 pCi/L, with some reported as high as 50,000 pCi/L. Pictures 9-11 are examples of an incorrectly vented SSD system (these systems were not installed at a naval installation). Picture 12 shows a properly vented SSD mitigation system.

Picture 9. Side wall discharge (not allowed).

Picture 10. Radon exhaust near window (not allowed).

Picture 11. Attic discharge (not allowed).

The argument put forward by most contractors in favor of not following the standards is that the added length of pipe decreases the performance of the radon system and increases the cost. With respect to performance degradation, simply installing a more powerful fan based upon the added resistance of the pipe generally suffices. It is also worth noting that some may point out that the prevailing standards cover only buildings of up to 3 stories. While this part is true, with proper engineering, a vent pipe can extend four or more stories (Picture 6). With respect to costs, it does cost more (e.g., more labor, and materials) to run a vent pipe above the eave. For example, the 4-story system shown in Picture 6 cost about 50% more than a single-story SSD system. However, a key point always missing is that there are no documented cases of re-entrainment issues when the standards were followed, but there are many examples of re-entrainment issues when they were not. Therefore, consistent with the standards, NAVRAMP requires all SSD mitigation systems to vent above the eves.

Picture 12. Properly vented SSD mitigation system.

4.3.2.8 PIPE STRAPPING AND CHANNEL

Durability studies of existing SSD radon systems within the Navy and USMC have identified corrosion of metal parts as a significant problem. This is particularly true at installations located on or in close proximity to salt water. The following sections provide recommendations for particular types of straps. Whenever possible, all strapping, channels, and fasteners need to be either galvanized or stainless steel (preferred).

To avoid corrosion problems, some contractors have switched to using plastic straps. Although these do not corrode, they do eventually pull apart (Picture 13).

Picture 13. Failure of plastic pipe straps (not recommended).

Another noted problem is straps that rely on friction to hold the pipes in place (Pictures 14 and 15). Over time, the thermal expansion and contraction of the pipe can cause the whole system to slide downward. This can result in the collapse of the boot or, in extreme cases, the pipe sliding into the fan.

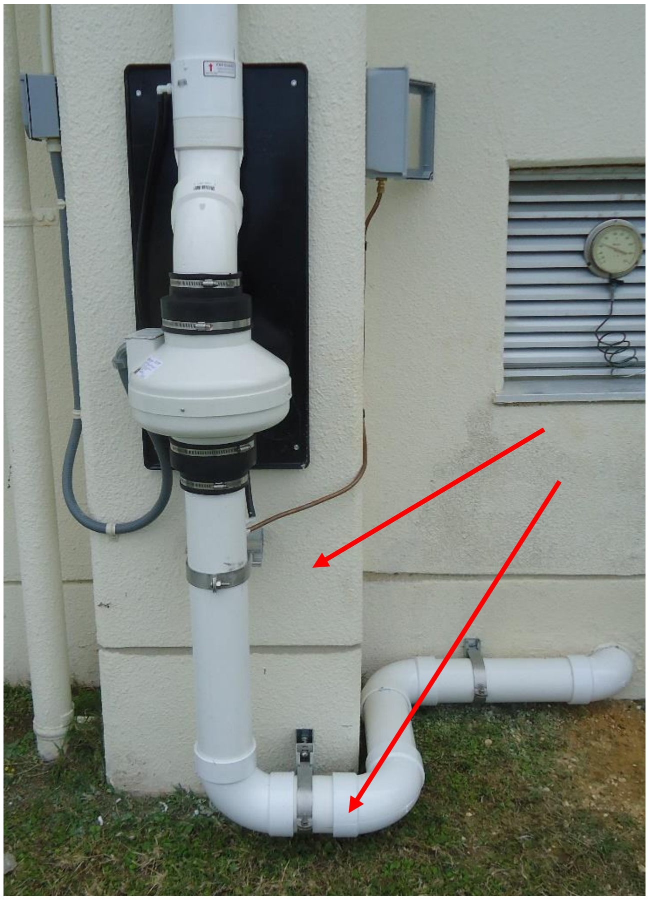
Picture 14. Clip on friction-based pipe strap (not recommended).

Picture 15. Wall-mounted friction-based pipe strap (not recommended).

Another commonly used strap is a thin gauge pipe strap (Picture 16) which is designed for metal electrical conduit. The noted problems with these straps are that the screw and bolt are light duty and cannot be tighten sufficiently to prevent the pipe from slipping over time. In addition, the single attachment point has been known to pull out during periods of high wind.

Picture 16. Electrical conduit strap (not recommended)

Within the Navy and USMC, the best long-term results have been obtained with a compression-type pipe strap (Picture 17) attached to 12 Ga slotted channel that is secured to the wall with 2 fasteners. Inspections performed on SSD systems installed >25 years ago with these types of straps and channels found no slippage or corrosion issues. Table 10 lists part numbers for the channels and straps shown in Picture 17.



Picture 17. Example of a compression pipe strap.

Table 10. Part numbers for Unistrut Corporation components

Item	Part number
7/8 in. slotted channel	P3300PPG
1⅝ in. slotted channel	P1000T
2 7/16 in. slotted channel	P5500
3¼ in. slotted channel	P5000
Pipe clamp 4 in. (stainless steel)	P11121 SS

4.3.2.9 SSD Electrical Considerations

The industry mitigation standards and the National Electric Code (NEC) requires that a radon fan must not be more than 50% of the circuit capacity and not be connected to a circuit that would exceed 80% (including the radon fan) of the circuits rated capacity. It is also recommended that the fan not be connected to a circuit which supplies power to refrigerator/freezer and other electrical equipment in which a prolonged power interruption would be catastrophic. National and local electrical codes also prohibit tapping into circuits which provide power to emergency lighting and smoke/carbon monoxide detectors. For Type 1 and 2 SSDs (Figures 27 and 28) power can typically be found by tapping into an existing wall outlet on the exterior wall. For Type 3 attic and roof mounted fans (Figures 29 and 30), lighting junction boxes in the attic are typically tapped into. In this case, the installation of an outlet within 6 ft of the fan would provide the option of the use of a corded fan. Fans mounted on the exterior of the building must be hard wired and use components that are suitable for wet locations. If power sources near the SSD system cannot meet these requirements, then a new circuit will have to be run to the breaker panel. Multiple fans can be powered by the same circuit provided they do not total to ≥ 80% of the rated circuit capacity. With the noted exception of corded fans, to facilitate maintenance and reduce the inconvenience to the residents or occupants, it is recommended that a switch be installed within 3 ft of the fan. Having the switch at this location would not require lock-out tag out procedures and having to de-energize the circuit prior to replacing the radon fan in the future.

Additional requirements include the following:

- The radon fan circuit must be a properly ground circuit.
- Wiring may not be in or chased through the mitigation installation ducting or any other heating or cooling ductwork.
- To facilitate fan replacement, the switch for the radon fan should be located within 3 ft of the fan.
    - Disconnect switches are not required for plugged fans.
- All wire shall be solid, 12 AWG (UFGS-31 21 13, 2018).

4.3.2.10 RADON MITIGATION FAN SELECTION CONSIDERATIONS

Radon mitigation using SSD is a balancing act between pressure and flow under the slab. Ideally a fan should be selected based on providing the highest vacuum with the highest flow. However, in general, as vacuum goes up, the flow will decrease. A consideration also in fan selection is the maximum operating vacuum. Fans that operate at or very near the maximum vacuum do not last as long as those operated at the mid-point of the performance curve.

Radon fans can be generally grouped into one of five general categories based on energy consumption and general use. The categories are:

- Low-power/low-wattage (14-20 Watts)
    - Porous subslab aggregate or soil
    - Maximum vacuum: 1 in. WC
    - Maximum flow: 140 ft^3/min
- Medium Power (37-71 Watts)
    - Large slab with porous subslab aggregate or soil
    - Small slab with less porous subslab aggregate or soil

    - Maximum vacuum: 2 in. WC
    - Maximum flow: 180 ft^3/min
- High-Flow (86-140 Watts)
    - Large slab with porous subslab aggregate or soil with numerous leaks
    - Maximum vacuum: 2.5 in. WC
    - Maximum flow: 350 ft^3/min
- High Suction (60-140 Watts)
    - Low permeability subslab aggregate or soil
    - Maximum vacuum: 5.5 in. WC
    - Maximum flow: 100 ft^3/min
- High Suction Blowers (200-700 Watts)
    - Highly impermeable aggregate or soil
    - Maximum vacuum: 50 in. WC
    - Maximum flow 75 ft^3/min

To determine the most appropriate fan to use, diagnostics, specifically the subslab permeability test (SPT) is performed (Section 5.1.8). From these diagnostics a curve can be generated and by overlaying manufacturer fan performance curves the appropriate model of fan can be determined. However, for installations with hundreds of mitigation systems to maintain, it would be more economical in the long run to make the effort to minimize the number of fan models being used. By doing so, the number of different types of fans needed for replacement and other associated parts could be significantly reduced. In most cases, for naval radon mitigation projects, fans can be broken into one of two groups low-pressure/high-flow and low-flow/high-pressure. For most SSD installations at naval installations experience has shown that either a high-flow fan or high-suction fan will suffice for most SSD systems. Ultimately, in cases where no other mitigation method is viable, an SSD equipped with a high blower may be the only solution.

4.3.2.11 SSD PERFORMANCE INDICATORS

Under NAVRAMP, all SSD mitigation systems must have a performance indicator that is easy to read or interpret to determine if the fan is working properly. To the extent possible, performance indicators should be located at an easily accessible location, at eye level, and as near to the fan as practical. The simplest and most common performance indicator, the manometer, deflects a volume of oil in a U-tube (Pictures 18 and 19). A variation of this type uses a magnehelic gauge (Picture 20). Others rely on an electrical pressure sensor to trigger either a warning light or an audible alarm (Picture 21). Based upon costs, the manometer is the least expensive of the performance indicators. Magnehelic gauges are easier to read but cost about 5 to 10 times as much as a u tube manometer and typically only last 7-10 years on the exterior of the building. The most expensive choice, the illuminated light box (Picture 21), relies on an electrical pressure sensor to trigger one of two LED lights (red indicating fan is off and green indicating fan is on). Maintenance for an illuminated light box is limited to infrequent replacement of the 10-year LED bulbs and pressure sensor. However, this is only a pass/fail indicator, meaning the fan pressure must be tracked using other means. To the extent possible, it is recommended that manometers be used wherever possible and the magnehelic and illuminated light box be used only in special cases where the manometer is not feasible.

Picture 18. Interior-mounted U-tube.

Picture 19. Typical external U-tube box.

Picture 20. Magnehelic performance indicator.

Picture 21. LED performance indicator.

4.3.3 Crawlspace Mitigation

For buildings with crawlspaces, submembrane depressurization (SMD) is usually the mitigation method of choice. An SMD consists of a membrane, vent pipe and an exhaust fan (Figure 33). To enhance the SMD vacuum and decrease energy loss, the plastic sheeting is sealed to the wall of the crawlspace. When the fan is activated, the radon soil gas is pulled from under the plastic sheeting and discharged above the roof. However, in uneven or large crawlspaces, a perforated pipe or geotextile matting connected to the vent pipe may have to be run under the plastic sheeting to extend the vacuum field.

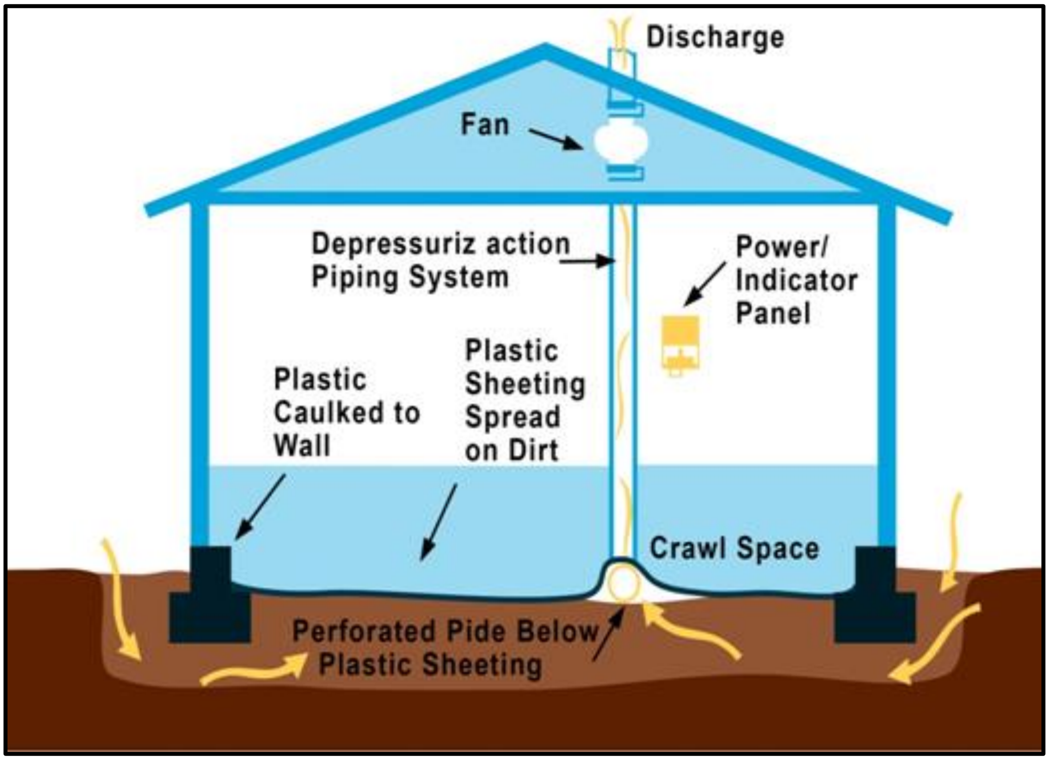


Figure 33. Basic submembrane depressurization system.

The minimum NAVRAMP specifications are that the systems comply as applicable with:

- *Radon Mitigation Standards for Schools and Large Buildings,* ANSI/AARST RMS-LB-2021
- *Radon Mitigation Standards for Multifamily Buildings*, ANSI/AARST RMS-MF-2021
- *Standard Practice for Installing Radon Mitigation Systems in Existing Low-Rise Residential Buildings*, ASTM E2121-13 (ASTM 2013)
- *Radon Mitigation*, UFGS-31-21-13 (UFGS 2018)

In addition, under NAVRAMP the following requirements must be met:

1. A health and safety review shall be conducted prior to the initiation of radon mitigation to determine if confined space permit and precautions are required.
2. All large rocks, sharp objects and debris shall be removed prior to the installation of the membrane.
3. As a minimum the polyethylene or rubber membrane shall be 3 mil thick cross laminated or 6 mil thick. If durability is in question, then 45 or 60 mil EPDM rubber (a polymer composed of ethylene propylene, diene monomer) shall be used.
4. All membrane seams will be overlapped by 12 inches and be sealed with a sealant appropriate for the membrane.
5. In traffic areas the membrane shall be protected with strips of EDPM rubber.
6. The edges of the membrane shall be sealed to the wall of the crawlspace and around support columns to a height of 12 inches. The use of pressure treated boards to more permanently secure the membrane is recommended.
7. All plumbing and other penetrations through the membrane shall be sealed.
8. Geotextile matting or 4-inch minimum perforated pipe tied into the suction point shall be placed under the membrane to help extend the vacuum field.
9. The radon mitigation fan shall not be installed in the crawlspace.
10. All exhaust stacks shall be at a minimum 4 inch, SCH40, solid or foam core PVC pipe.
11. A tee or a purpose-built riser shall be installed under the membrane.
12. Warning labels shall be posted near the entrance of the crawlspace and in visible locations on the membrane. As a minimum all system lettering shall be not less than ¼ in. in height and shall be of a color in contrast to the background color to which the lettering is applied. The label shall state “Radon Reduction System Membrane Do Not Alter or Damage” and whom to contact if the membrane has been damaged.

If SMD mitigation is not viable because of access or other issues, crawlspace depressurization (CSD) is typically the next method of choice. In this method, all pathways between the floor above must be identified and sealed. A modified blower door test is typically performed (Section 5.1.5) before, during and after the sealing to with the aid of a smoke pencil more easily identify smaller pathways and monitor sealing progress. Included in the sealing would be all crawlspace passive vents, any other openings to the outside in the crawlspace wall and all supply and return air duct work. Once sealed, a system very closely resembling an SSD system (Section 4.3.1) is installed. All exhaust from the crawlspace must be exhausted above the roofline and the mitigation fan must be on the exterior of the building, in the attic or on the roof of the building. Fan size for the system will depend on the volume of the crawlspace and its leakage. However, the selected fan should provide a minimum of 10 Pa pressure differential between the living area and the crawlspace. CSD mitigation should never be used if asbestos is present in the crawlspace.

Another technique similar to CSD is crawlspace pressurization (CSP). In this technique, sufficient air is blown into the crawlspace to pressurize it. This technique although effective has several noteworthy problems. In cold climates, the introduction of outdoor air may result in the freezing of exposed pipes and a cold floor in the living area. Therefore, the pipes and floor must be insulated. In hot, humid climates the introduction of the outdoor air will cause condensation leading potentially to mold and rot of wooden structural members. In addition, odors from the crawlspace have been known to permeate the living space. For these reasons, CSP is not recommended under NAVRAMP.

4.3.4 Energy Recovery Ventilation Mitigation

ERV mitigation works solely on the principle of indoor volume dilution. This is accomplished by the use of a commercially available unit (Figure 34) that exchanges a fixed volume of indoor air with an equal volume of outdoor air (units' range in capacity from 100 to 100,000 cfm). Selection of the correct size unit is critical and is based on the cubic volume of the room or building being ventilated, the current ventilation rate (measured in ACH), and the initial radon concentration. Empirically speaking, doubling the ACH in the room or building will reduce the radon levels by 50%.

Although ERV is a proven mitigation technique, installation and operational costs (e.g., routine maintenance on filters, drive belts and motors, and desiccant wheel) are significantly higher than for SSD mitigation (Figure 22). Furthermore, because of conditioned air loss during the exchange process (most units typically recover 80%), the energy penalty can be quite high for high-capacity units. This energy deficit may become problematic if the existing HVAC system lacks the capacity to make up for the loss.

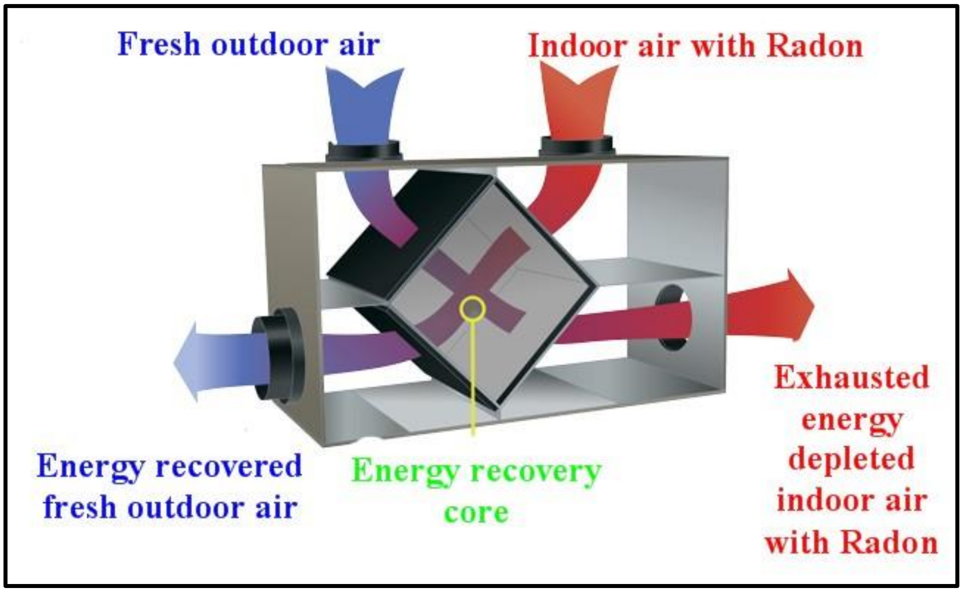


Figure 34. Energy recovery ventilation overview.

4.3.5 Supplemental Air Mitigation

Supplemental Air Makeup (SAM) is a mitigation technique developed by the Department of Energy (DOE) for niche applications within nonresidential Navy and USMC buildings. The most common application of this mitigation method has been the mitigation of arms and Sensitive Compartmented Information Facility (SCIF) rooms within buildings where SSD could not be used for technical or security reasons. However, more recently, it has been successfully applied to mitigate interior rooms in buildings where HVAC adjustments, replacement or repair were cost prohibitive.

For individual room mitigation in nonresidential buildings, a SAM system can be installed to control radon by increasing a room's ventilation rate. Typically, a SAM system draws 75 to 500 ft^3/min of conditioned air from an adjoining hallway or large room known to have low levels of radon and discharges it into the room (Figure 35). Unconditioned air from outdoors or from within the building should never be used as the source air for this mitigation technique.

Although a SAM system is the least complex of all active mitigation systems (i.e., typically it consists of only a fan and two short pieces of ductwork), for it to work properly, significant pre-mitigation planning must be employed. The first step in SAM design is to select the best approach for radon control in the room. Rooms that are typically open for most of the day are better suited for a ventilation approach requiring more make-up air. Whereas rooms that are closed most of the day can be more easily pressurized typically using a much smaller volume of air.

To design a ventilation SAM system, one must first estimate or, preferably, measure the room's air exchange rate (ACH) and then perform a series of calculations that include the room's volume and its current radon level (EPA 1988b, 625/5-87/019). From these calculations, the appropriate capacity for the in-line ventilator can be ascertained. For a pressurization SAM, the objective is to provide sufficient make-up air to make the room at least 4 Pa positive relative to the subslab pressure. To accomplish this, known air volumes are added to the closed room with concurrent differential pressure measurements referencing the subslab.

The next step is selecting an intake and exhaust location for the system. In most cases, noise caused by air intake in a hallway does not cause most of an issue since they tend to blend in with other background noise. However, exhaust into the room can be both a noise and occupant comfort problem unless proper caution is taken. To the best extent possible the room exhaust should be located as far as practical from where the people sit or work.

For duct work and inlet and outlet port sizes consideration must be given for both potential noise (air intake and exhaust can generate noise) and occupant comfort caused by the exhaust air velocity.

Although standard organizations (e.g., ASHRAE) provide guidelines for appropriate duct and intake/exhaust sizes for specific volumes of air, these are specifically provided for indoor conditioning applications, not radon mitigation. Ideally for SAM, the air flow into the room needs to be as undetectable as possible. To accomplish this SAM duct work and intake/exhaust grills need to be size larger than ASHRAE recommendations. For example, 200 ft^3/min of air typically would be typically transported through an 8 in. round duct which would result in a detectable exit velocity of 572 ft/min. However, if a 10 in round duct is used for the same volume of air, exit velocity would be 367 ft/min which may or may not be detectable depending upon the background noise in the room and the current room air velocity.

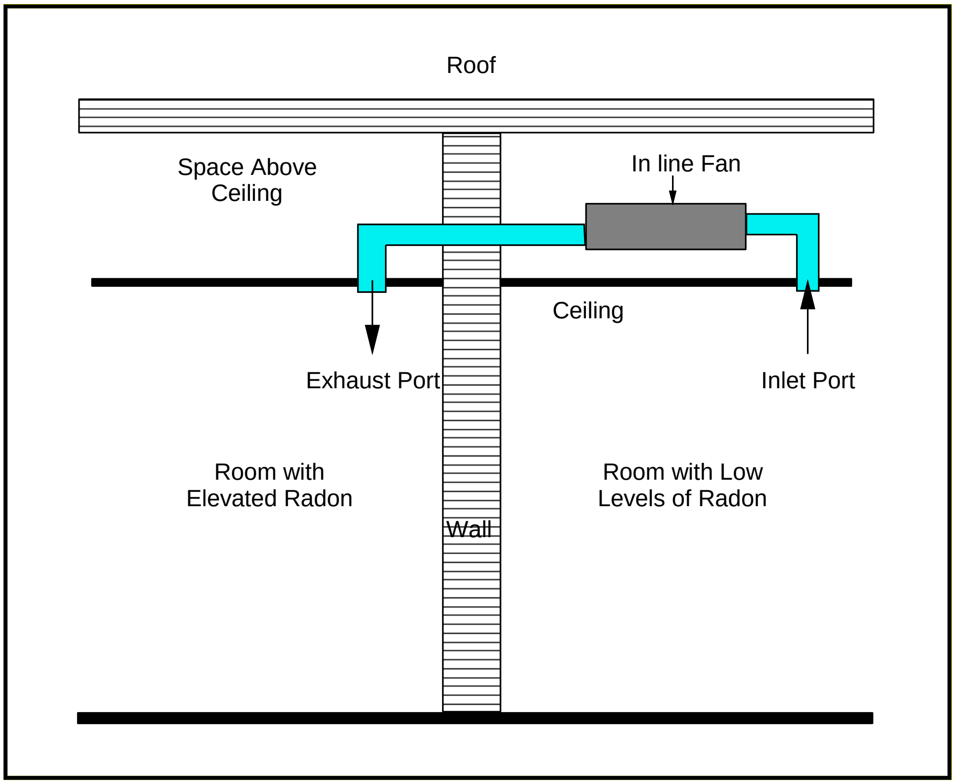


Figure 35. Supplemental air mitigation system.

A drawback for this mitigation technique is its range of applications. Typically, for SAM to be a viable option, the room in question must have a radon level <20 pCi/L, be <3,500 ft^3 in volume, and have a low pre-exiting air-exchange rate (e.g., <0.2 ACH). In addition, the room must be located near a large room or common area from which the required volume of conditioned air containing a low level of radon can be withdrawn without a significant risk of depressurization.

In addition to the design parameters, particular attention must be paid to noise and occupant comfort. Because these systems are usually used in single or double offices, the noise generated by the discharge of the supply air may pose an inadvertent distraction to the occupant(s). Therefore, the supply diffuser, in addition to being aesthetically pleasing, must afford the minimum amount of noise. Another important consideration is the location of the discharge point. The discharge air velocity from a typical SAM system is comparable to that of a forced-air system. So, to the extent possible, the discharge needs to be in a location that would not appreciably increase the air velocity in the primary work areas.

4.3.6 Air Cleaner and High-Efficiency Particulate Air Mitigation

Another post-entry mitigation method involves the use of high-efficiency air filtration systems that remove particulates from air (similar in design to the portable HEPA filtration units used by asbestos abatement companies). These units are commercially available (air filtration units commonly found in consumer retail stores do not meet ASHRAE Standard 52.2-2007 [ASHRAE 2007] for this application) and are typically integrated into the existing return air ducting. Like ERVs, these units need to be properly sized (unit and installation costs are comparable to ERV) for the required air volume. The long-term operational cost of HEPA typically exceeds that of ERV because of the need to frequently replace (e.g., weekly or monthly as required) the highly specialized filters (HEPA filters commonly found in consumer retail stores do not meet ASHRAE Standard 52.2-2007 [ASHRAE 2007] for this application).

Currently EPA (EPA 625/5-87/019, and Jalbert and Fisher 2008, US EPA correspondence to Douglas County School Board, Minden, Nevada in Appendix A), UFGS-31 21 13 (Section 2.1.1.4 November 2018) and ANSI/AARST mitigation standards (ANSI/AARST RMS-LN 2020) do no support the use of portable air cleaners and HEPA filtration units as a means of radon mitigation. Radon is a gas and cannot be removed by filtration from indoor air. However, its decay products which attach to dust and other airborne particles (commonly referred to as the attached fraction) can be removed. The radon daughters which are attached to ≥ 10-micron particles are the ones that are commonly measured using working level meters (Section 3.4.6). Most residential studies have shown that the equilibrium ratio (the percent of daughters in the air attached to these ≥ 10-micron particles) ranges between 40 to 50%. The unaccounted-for daughters, those that are not counted by a working level meter are referred to as the unattached fraction. A common assumption is that most if not all of the unattached fraction deposits quickly and irreversibly onto surfaces within the room and out of the breathing zone. Currently, there is no conclusive science to support this assumption and there are currently no analytical methods to prove or disprove it. Although it is acknowledged that the reduction in the attached fraction concentration would lower the risk from exposure to the radon daughters attached to particles down to a size of 0.3 microns, there is a high probability that in the absence of these particles once removed from the air, that the constantly generated radon daughters would establish a new equilibrium but on < 0.3 micron particles (microparticulates) or form molecular complexes which can then be inhaled and deposited into the lung. Estimates of the lung dose efficacy by these daughters attached to microparticulate or formed molecular complexes range from between 20 to 30 times greater than those attached to a >0.3-micron particle. Consistent with EPA and ANSI/AARST technical guidance, NAVRAMP does not recognize air cleaning as a means of reducing the risk from radon and is not recommended as a mitigation method.

4.3.7 HVAC Mechanical Adjustments and Repairs as a Mitigation Method

Ventilation is a balance between intake, exhaust, localized distribution of the conditioned air and energy. If a mechanical issue is causing elevated radon levels, it usually falls into one of the following categories: lack of fresh-air, localized imbalanced supply or returns, HVAC energy setbacks during unoccupied hours or excessive exhaust.

A common misconception is that all HVAC units have a reserve capacity which can condition added fresh-air volume or that all fresh-air intakes can always be set at maximum volume. This is not true since oversized units tend to short cycle resulting in broad temperature and humidity excursions, cost more to purchase and to operate. With respect to fresh-air intake duct size there are many designs and technical reasons that it may oversized (e.g., duct static pressure, noise reduction etc.) that may not be clearly documented in the mechanical drawings. Also, in older buildings it is not uncommon for the HVAC unit to be replaced while keeping the original fresh-air intake duct. Therefore, the mechanical drawings and specifications must be consulted prior to making any fresh-air adjustments.

Another consideration is the HVAC age. Like other mechanical devices, performance decreases over time. It is not unusual for a 5-year-old HVAC to have a 5% reduction in conditioning efficiency with older units having significantly more. Therefore, there may be a reason why the volume of fresh-air intake has been reduced and causing the elevated radon levels. It is important to note that ill planned adjustments made to HVAC units within the DoD and Coast Guard has resulted in mold out breaks, loss of mission critical electronic equipment, severe occupant comfort issues and significant damage to the HVAC unit. It is highly recommended that both an HVAC engineer and the facility HVAC shop be consulted before any actions are taken to increase or decrease ventilation volumes.

In any proposed mitigation approach using mechanical balance or adjustments, the installation mechanical shop should be consulted. At most installations, the mechanical shop has the as built drawings for all mechanical systems at the installation. In most cases, these drawings have been updated to include any changes or modifications made to the building mechanicals. Maintenance and service call records can also provide insight as to the overall “health” of the current unit. Most mechanical shops also maintain records regarding future mechanical replacements. If a mechanical unit is going to be replaced within the next year or two, another mitigation option may be more prudent. Prior to performing any supply/return balancing, fresh-air make up or exhaust volume changes shop personnel should be consulted to ensure that they know what is being proposed or done.

It is important to note that most residential mechanical systems in the United States are designed solely for heating and air-conditioning (HAC) of indoor air. Unlike HVAC systems, HAC systems do not provide outdoor makeup air to offset air losses that result from the operation of the building exhaust systems. For this reason, negative shell pressures can occur in residential homes with tight building envelopes during the episodic operation of clothes dryers, bathroom and kitchen exhaust fans, and powered combustion flue exhausts. Although modifications can be made to most HAC systems for the intake of outdoor air, there is a risk that the HAC system may not have the capacity to adequately condition this added load (e.g., heat, cool, and dehumidify). This in turn could lead to occupant comfort problems and, in more serious cases, moisture control issues. Therefore, HAC systems should not be modified for the inclusion of fresh air without consultation with a qualified HVAC engineer.

4.3.7.1 HVAC Mechanical Balance or Adjustments

In general, there are two key components in mechanical balance, the indoor balance of the supply and return air and the balance between fresh-air intake and exhaust. In a properly designed and maintained forced air system, the supply and return air volume is evenly distributed and drawn throughout the building. In the most simplistic designs, it is a closed loop system meaning the supply and return air volumes are equal. The distribution and balance of these air streams is controlled by diffusers within each area. Optimal ventilation is usually achieved when the supply and return air volumes are at the design specification. Within a forced air system, the volume of supply air is finite meaning that if a room occupant adjusts a diffuser to get more air, the area towards end of the main supply duct will get less. Conversely if the occupant reduces the supply the air into their area, the area towards the end of the supply duct will get more. In most forced air systems, returns are strategically placed and sized to draw in the designed air volume. If that design volume cannot be met, that area will be depressurized. Conversely, if a return is blocked or restricted, the area will be slightly pressurized. In both cases the total volume of air being recirculated throughout the system will be less than the design volume. It is important to note that radon levels can become elevated in areas or rooms with low ventilation and/or negative pressure relative to the subslab.

Prior to attempting to address the balance issue, a review of the building mechanical drawings should be performed. A key question to address is whether the current design is suitable for its current use. An inspection of the blower unit should then be performed to measure its current supply capacity. Like all mechanical devices, performance decreases with age and in some cases the current blower may no longer be able to provide the original design air volume. In older buildings, an examination of the duct work should be performed. In some cases, the buildup of dust and dander within the duct work can be significant enough to result in air friction loss and may require ductwork cleaning. Another issue with older duct work is deterioration. It is not uncommon in older ductwork to find broken connections and leaks. These need to be repaired or replaced in order to ensure that 100% of the supply and return air is being delivered.

After the blower and ductwork have been restored to original design specifications, a flow hood (Section 5.1.7) diagnostic is then performed. As the diagnostic is being performed, the supply and return air volumes for each diffuser is adjusted per design specifications. Once restored, the entire building must be retested for radon.

Although resetting the HVAC fresh-air makeup to the original design specification can be effective in the short term, long-term studies conducted by DOE have found problems with sustaining mitigation over the long-term. For example, in one group of naval buildings that were mitigated by restoring the fresh air to the original design parameters, 50% of the buildings were found not to be mitigated after 5 years. The primary reasons for the mitigation failure were:

- Problems controlling indoor temperature and humidity.
- New energy conservation rules which required higher indoor temperatures during the cooling season.
- Lack of system maintenance specifically clogged intake filters.
- Accidental reduction of fresh-air volume by the maintenance staff.
  - System labelling and the education of maintenance staff resulted in only marginal improvements.

An often-overlooked issue in this mitigation approach is the building occupants. In buildings that are out of supply/return balance it is not unusual to determine that the building occupants were adjusting the diffusers. In most cases there was a reason for them to make diffuser adjustments, too cold, too hot or too much noise being the most common complaints. Rebalancing in most cases will resurrect the previous occupant comfort issues and could potentially make long-term mitigation difficult to maintain. In quite a few cases at naval installation successful mitigation via supply/return balance has been defeated by occupants with comfort issues after a few days or months. Although nonadjustable diffusers are commercially available, there is no easy way to protect the forced air system from the use of cardboard and duct tape.

The other component of mechanical balance is fresh-air intake and exhaust. In most HVAC designs the volume of fresh air is slightly greater than the total exhaust volume. The primary reason being that a building under a slight positive pressure will retard unconditioned outdoor air entry. However, it is also interesting to note that to date no naval nonresidential buildings with a (+) 4 Pa shell pressure have been identified as having elevated radon levels. Unfortunately, over time and for various reasons most nonresidential buildings will develop a negative shell pressure. The most common reason for this being performance degradation of the heating and/or cooling systems which require a reduction in fresh air make up to maintain appropriate indoor temperature and humidity. Another commonly cited reason is energy conservation measures. Older HVACs were designed with specific indoor temperatures in mind. Indoor dehumidification is mostly performed by the AC system and the coils are sized to remove a specific amount of moisture assuming a specific indoor temperature. Therefore, an HVAC designed to maintain a 74^{o}F indoor environment cannot remove the same amount of moisture at 78^{o}F. Therefore, the volume of fresh air must be reduced to maintain indoor humidity. In cases of older equipment and installation energy savings requirements, a workable mechanical solution using an increased volume of fresh air may not be possible.

Another energy conservation consideration is the replacement of the current central heating and/or cooling unit with a more efficient unit. There are a lot of considerations that must be taken into account in selecting a replacement unit. Current building heat and/or cooling loads, current ventilation requirements etc. Also, to save on energy costs, the replacement unit will almost always be smaller and have a lower dehumidification rating. Therefore, the volume of fresh air will be lower than the original specification. Unfortunately, in some central HVAC unit replacement projects the current exhaust volumes are not considered. This coupled with reduced fresh-air volumes greatly enhances the probability that the building will have negative shell pressure.

Another consideration is the current exhaust volume. In older buildings it is not unusual to find exhaust for the following reasons:

- The exhaust system was designed to remove cigarette smoke.
  - Not unusual for older MWR facilities
- After failure, the original exhaust blower was replaced with a higher capacity one.
  - Most common reason was that the original exhaust blower was not available.
- The previous mission of the building required high exhaust volumes.
  - A current office building may have once been a repair shop.
  - Communication facilities which were designed to exhaust heat from vacuum and cathode ray tubes.
- The former use of a room in the building required high exhaust.
  - Former shower room, nail/hair salon, kitchen, or animal kennel.

Prior to any other corrective action, the building's exhaust system needs to be inspected and evaluated first. A qualified HVAC engineer can easily determine if the existing exhaust volume is excessive and provide a more suitable exhaust volume. Keep in mind that every ft^3/min of exhaust air requires an equal volume of make-up to maintain shell pressure parity.

For buildings in which a qualified HVAC engineer has determined that the exhaust volume is excessive and provided a minimum volume, CRM diagnostics (Section 5.1.9) are performed. In most cases, by turning off the exhaust blowers in sequence or in combination (do not drop below the minimum exhaust volume) the correlation between radon and negative shell pressure can be established. Once this correlation has been established, as circumstances dictate, it is recommended that the oversized exhaust blower(s) be either permanently removed or replaced with the correct size exhaust blower. It is not recommended to simply turn it off and provide signage.

In most cases where high levels of exhaust are required and the existing HVAC cannot handle the required fresh-air volume, then a supplemental conditioning unit (precooler) can be added to condition the added fresh-air. These supplemental units are commercially available and are considered off the shelf options for most HVAC units.

In extreme exhaust cases, the installation of a standalone DOAS may be required. For example, in a 9,000 ft^2 combination office and repair shop all 7 rooms had radon levels ranging from 20-30 pCi/L. Because of cleaning solvent use in the repair shop a 3,000 ft^3/min exhaust blower was required and had to be left on 24/7. The building shell pressure was measured at (-) 60 Pa which eliminated SSD mitigation. Redesigning and replacing all of the building's HVAC and exhaust system was going to be very expensive, would have taken over a year and would have caused an interruption of several months for a nonrelocatable, mission critical organization. The solution was to install a standalone, off the shelf, centrally ducted 8-ton DOAS unit which could be installed without mission interruption. The DOAS unit provided 3,500 ft^3/min of conditioned fresh-air and slightly pressurized the building. Postmitigation testing found all rooms < 0.5 pCi/L.

In buildings without central ducts, forced air HVAC systems, it is typical to find mini-split or packed terminal heat pump or AC units. The key advantage of these units is that they are very energy efficient and have lower operating costs. Although some of these units are factory equipped with a fresh-air intake and a dehumidification cycle, most only provide heating and/or cooling and do not perform any appreciable added dehumidification. To save manufacturing costs, typically only one chassis is built for use with many different types of compressors and other optional features. Therefore, it is not uncommon to find a fresh-air damper, or a knockout for the installation of a fresh-air makeup present in the chassis. The presence of these features should never be interpreted as meaning that the unit has the capacity to condition any volume of outdoor air. Activation of these features should never be performed unless it has been confirmed by the manufacturer that the appropriate compressor has been installed.

In summary, for nonresidential buildings with existing fresh-air intake ducts, increasing the fresh-air volume to either dilute the radon, pressurize the building to retard its entry, or negate a negative building shell pressure are all potential options. To determine the correct volume of air required, a blower door test is performed (Section 5.1.5). An evaluation of the current heating and /or cooling unit is then performed by a qualified HVAC engineer to determine if the added volume of fresh air will cause any temperature or humidity issues. It is essential that the changes will not result in the building being ≥ 60% RH to prevent mold growth and that the temperature be maintainable within the prescribed limits. If the addition of the additional outdoor make-up air is plausible, only then should the adjustments be made. After the adjustments have been performed, the entire building should be retested. If the corrective action involved an increase in the volume of fresh-air, concurrent with the postmitigation test, temperature and humidity measurements (continuous preferred) to ensure that the added air volume is not exceeding the required limits. At installations with seasons, temperature and humidity measurements are also recommended during each of the seasons to ensure no seasonal issues.

4.3.7.2 HVAC Energy Setbacks

Over the past 20 years there has been an increase in the number of HVAC units which incorporate energy conservation features. Some of these features can enhance or decrease the radon levels during occupied periods. In certain cases, deactivating or modifying these features can mitigate the room or building but with a loss of energy savings. In the most basic examples, an electronic controller during unoccupied times that will do one or more of the following:

- Reduce or eliminate fresh-air intake during unoccupied periods.
- Depending upon the season, allow for the indoor temperature to rise or fall.
- Have the unit operate at a lower conditional setting (dual stage compressors) and/or lower blower settings.

In most buildings the energy set back is typically set at the point at which the last person is expected to leave the building at the end of the workday. Conversely 1 to 2 h prior to reoccupancy the energy set back is turned off and normal occupied HVAC operations resume. For most buildings, the energy set back is applied typically between 1800 till 0600 the next day. Some of the more advanced controllers can also be programed to also include energy setbacks for the entire weekend and scheduled holidays. In documented studies performed by DOE, year-round heating and cooling costs can be reduced in some locations by up to 40% using energy setbacks. To ensure minimal ventilation during set back hours, some or all of the exhaust systems are left on. Within buildings with tight envelopes the combination of reduced fresh-air intake, and negative shell pressure can in some buildings greatly enhance the radon levels during the unoccupied periods. In some cases, over extended energy setback periods (e.g., all weekend and scheduled Monday holidays) radon levels in excess of 100 pCi/L have been observed. A popular misconception is that once the energy set back has been turned off, the HVAC will reduce the radon levels to acceptable levels for the entire occupied period. But, in reality it is much more complicated and requires extended CRM diagnostics to establish (Section 5.1.9) what the radon levels are doing after the energy setback has been turned off. To meet the 4 pCi/L mitigation criteria, the integrated average for the workday would need to be < 4 pCi/L. Which means that a ≥ 4 pCi/L from 0600 to 0800 would be acceptable provided the rest of occupancy period was sufficiently lower to average below 4 pCi/L. However, in cases where the energy set back is operating over the weekend, the radon levels at the start of the workweek on Monday may not be below 4 pCi/L for most if not all the occupancy period. A common approach to remedy this potential problem is to simply have the energy set back turn off earlier to ensure that the radon levels are < 4 pCi/L consistently prior to occupancy even though this approach reduces the overall energy savings. For example, in a 10,000ft^2 building one room was found to have elevated radon. By shortening the energy set back by 2 h per workday, the radon levels in the room were reduced to < 4 pCi/L for the entire occupancy period. However, the additional annual energy costs for the entire building totaled about $3K more per year. A cost benefit analysis determined that an SSD system with a 60 W fan as being the best economical choice ($70/year) over the long-term.

Conversely within a similar sized building, with 8 of 10 rooms having elevated radon levels, shortening the energy set back by 2 hours-maintained radon levels to < 4 pCi/L for all rooms throughout the occupancy period. A key consideration in the mitigation of this building was that it was scheduled for whole building revitalization and repurposing within the next 3 years. Incorporation of RRNC features during the revitalization was determined to be feasible. In this case, 4 SSD systems were going to be required to mitigate. A long-term cost benefit analysis determined that the installation costs of the 4 SSD systems was more expensive than operating under reduced energy setback for the next 3 years and incorporating RRNC features during renovation.

Because radon levels can vary from day to day and from season-to-season and by different HVAC settings, a series of CRM diagnostic measurements would be required throughout the year to establish a baseline. For each measurement event, it recommended that a 7-to-14-day CRM diagnostic measurement be performed. This series would also need to be repeated later after any HVAC adjustment and for required NAVRAMP operation and maintenance and monitoring testing.

It is important to note that in some buildings, a private company may have installed new HVAC equipment or electronic controllers to reduce the conditioned air energy consumption. In some cases, the company is reimbursed for the installation based upon the energy savings during a fixed contract period. Deactivation or modification of the equipment would be considered a breach of contract and perhaps subject to legal action. Another complication can be the installation's energy conservation program. In the more stringent cases, command has set mandatory goals for energy reduction. Deactivation in some cases can double the heating and cooling energy consumption for a building. For these reasons, the installation energy conservation office should be consulted prior to any modifications or deactivation of energy saving features.

In summary, to determine if radon levels are consistently < 4 pCi/L during the occupancy period, a series of 7-to-14-day CRM diagnostic measurements performed throughout the year may will be required to demonstrate that the NAVRAMP radon mitigation goals are met. Although energy set back times can be shortened, the added cost of operation may exceed other mitigation methods over the long-term.

4.3.7.3 HVAC Maintenance and Repair

In some cases, the elevated radon problem may be directly linked to a routine maintenance item (e.g., clogged filters), or non-functioning or missing part of the HVAC. Examples include nonfunctioning or purposely blocked fresh-air intake ducts, nonfunctioning control actuators, disabled or nonfunctioning electronic controller components and clogged return air filters. For these types of problems, the facility maintenance shop should be informed, and arrangements made for its correction. Mechanical repairs to an HVAC unit should never be performed without knowledge and consent of the installation HVAC shop.

Although mechanical repair is a recognized radon mitigation technique and subject to routine inspection and periodic retesting, the reality in this specific case is that the elevated radon levels were the direct result of a maintenance issue or broken part. This is self-evident with a successful postmitigation test after the maintenance and/or repair has been completed. In cases of routine maintenance items (e.g., replacing filters, cleaning screens etc.) it is imperative that the installation mechanical maintenance shop agrees to incorporate these items into a predetermined maintenance schedule.

Within buildings which have been mitigated by HVAC maintenance or mechanical repair a surprising finding was how durable these actions were. Follow-up testing within these buildings have found that if proper maintenance and repairs are performed, none have developed any elevated problems over a 10-year span. For that reason, under NAVRAMP, if maintenance and repair corrected the radon problem, and the prescribed maintenance is followed, then there is no need to perform periodic inspection. In addition, in this case, radon testing is only required every 5-years during the scheduled monitoring phase. A good example of this type of mitigation was a 2,000 ft^2 fast food restaurant which had annual radon levels between 20 to 25 pCi/L. During mitigation diagnostics it was observed that the shell pressure varied from (-) 6 Pa to (-) 30 Pa which correlated well with the operation of the cooking grill exhaust hood. The exhaust hood in question came with an optional air curtain which supplied unconditioned air to negate the hood exhaust. Examination of the air curtain fresh-air intake filter found them totally clogged. Replacement of these filters and cleaning of the mostly clogged HVAC intake screen resulted in the building being pressure neutral. Postmitigation testing found all areas < 2 pCi/L.

4.3.8 Dedicated Outdoor Air System

A dedicated outdoor air (DOAS) system is a type of commercially available HVAC system that delivers a fixed volume of conditioned outdoor air into a building. These units are commonly used in hospitals, laboratories, restaurants, and industrial buildings where a high indoor air ventilation turnover rate (e.g., >2 ACH) or a large volume of conditioned outdoor makeup air is needed. Like ERVs, commercially available units are available over a considerable range (100 to 100,000 cfm) and can be customized to meet almost any ventilation requirement. Also, like ERV, a DOAS controls radon principally by dilution but can also be used at higher volumes as a Type 2 SP system (Section 4.3.1). Typically, these units consist of two parallel systems: a single pass dedicated outdoor air ventilation system that handles latent heat loads, and a parallel system to handle sensible heat loads. DOAS units can be configured with or without building return air (Figure 36). However more recently some DOAS units have included reconditioning some return air from the building. Others use the return air to regenerate the desiccant wheels (used to remove outdoor moisture). Because of its high installation and energy costs, the DOAS is not a commonly used radon mitigation method and is considered only when all other methods of radon control have been ruled out. Examples of situations in which a DOAS would be considered are a building under significant preexisting negative shell pressure (e.g., ≤20

Pa) in which the existing building mechanical systems cannot be modified or replaced to meet current heating or cooling load conditions (shell pressure is measured from the indoors relative to the outdoors using an electronic micromanometer). Another application is within a building with a low ventilation rate (e.g., <0.2 ACH) in which the energy loss created using an ERV cannot be handled by the existing HVAC system.

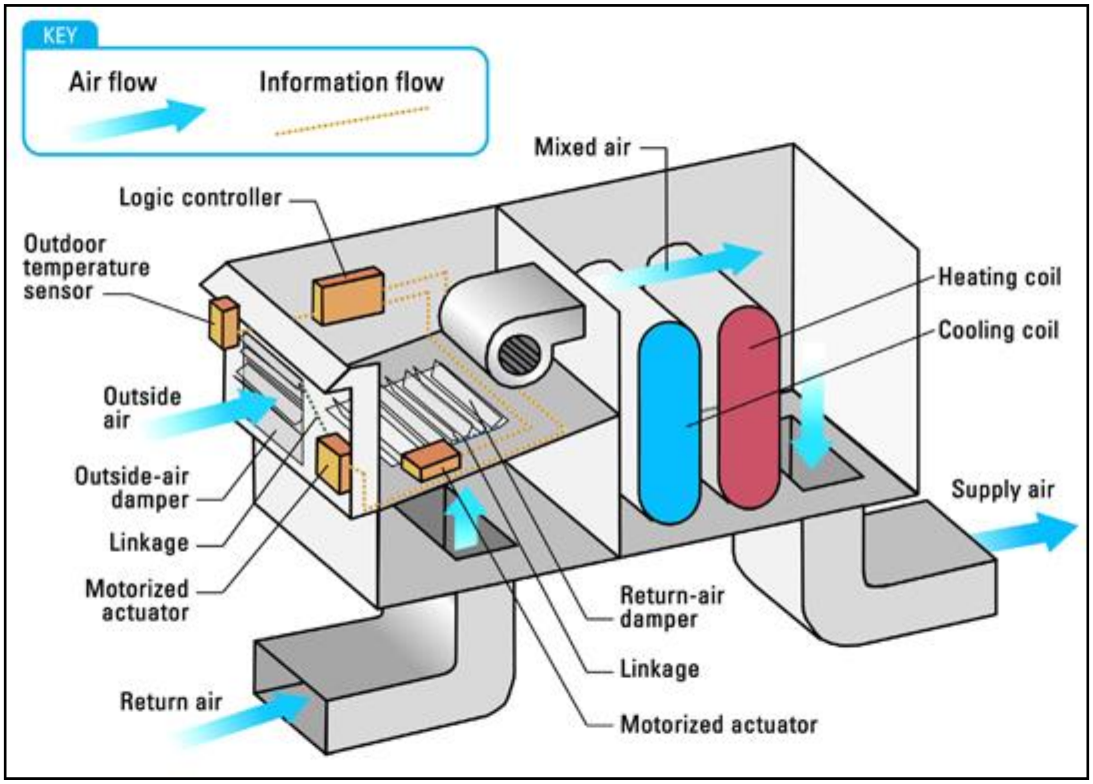


Figure 36. Flow diagram of a DOAS with return air features.

4.4 MITIGATION OF RADON IN WATER

Radon can be removed from water using one of two methods, aeration or granular activated carbon (GAC). Point-of-use devices such as those installed on taps or under sinks will treat only a small portion of the water and are not effective in reducing radon in water. The best method, aeriation, uses either water nebulization (spray) or bubbling outdoor air to remove radon. This method is the most effective (removes up to 99% of the radon and has no known upper limit for effective radon removal) but it is also the most expensive and requires regular maintenance to prevent clogging and the buildup of bacteria. In addition, the units are also noisy and need to be located as far as practical from occupied dwellings. GAC on the other hand is cheaper to install but is not appropriate for radon concentrations > 20,000 pCi/L. In addition, GAC will concentrate the radon daughters and can emanate significant gamma radiation. Therefore, it needs to be in a low occupancy room or area. GAC also needs a fixed retesting schedule at 1 and 6 months after installation and every year until the carbon is replaced. In most cases the carbon will last 1 to 5 years. It is important to note that the spent carbon will be radioactive and will need to be checked and may require special handling before disposal. As for availability, the equipment to install aeration or GAC are commercially available through most radon supply businesses.

4.5 RADON MITIGATION WITHIN SENSITIVE COMPARTMENTED INFORMATION FACILITY

Radon mitigation within Sensitive Compartmented Information Facility (SCIF) can be a challenge, but it is not impossible. Within the Navy and USMC, a SCIF can be in a particular room or be an entire building. In general, there can be no penetration from a nonsecure area or from the outside into a SCIF. Therefore Type 2 and 3 SSD systems and Type 2 SP systems will not be allowed. In addition, the electrical power for the mitigation system must come from a nonsecure electrical panel. In most cases, the bottom of the slab is the end point of the SCIF. Therefore, a Type 1 SSD would be acceptable in most cases. If SSD is not viable, a ventilation or pressurization solution would be the only choices. If the SCIF has a preexisting forced air supply duct coming into the room, increasing the supply air or installing an inline duct booster fan to increase the ventilation or pressurize the room or areas would be an acceptable method. In larger SCIFs which have a return forced air intake, reducing the return while maintaining or increasing the supply air would pressurize the room or area as well. If supply and/or return air adjustments are made, there may be an impact on comfort within other rooms in the building. Therefore, a rework of the building's mechanicals may be required. If the SCIF is a whole building and only a few rooms have elevated radon levels, then SAM would be an excellent choice. For whole SCIF buildings with elevated radon levels, ERV or whole building pressurization would also be an option.

In most cases getting unrestricted copies of building plans for buildings with a SCIF is very difficult. Although the review of the plans by a properly vetted person is not out of the question, the level of detail which can be transcribed to handwritten notes may be limited and may require review prior to leaving the SCIF. In most cases, the entry of non-SCIF personnel into the SCIF requires the suspension of all operations. Therefore, an advance plan should be developed to accomplish the trip's goals in the shortest time period possible.

To perform mitigation diagnostics or mitigation within a SCIF, the appropriate security personnel will need to be consulted during the early planning stages of the mitigation project. With advance planning and notification, most mitigation diagnostics techniques can be performed within a SCIF. However, all the electronic instruments (micromanometer, flow hood, radon sniffer, etc.) will need to be inspected prior to being taken into the SCIF. Electronic instruments which have recording features, WIFI or Bluetooth will not be allowed.

Once a mitigation plan has been developed, the local security personnel may not have the authority to allow for its installation. Approval from higher level security personnel not located at the installation can take some time (e.g., days to months). Therefore, mitigation planning in SCIFs needs to be initiated as early as possible.

5. MITIGATION DIAGNOSTICS

5.1 OVERVIEW OF MITIGATION DIAGNOSTICS

For residential and nonresidential buildings, there are many alternatives for both passive and active radon mitigation. Selection of the optimal mitigation system for a building is essential for a long-term, cost-effective solution. If a poor selection is made, the radon problem may not be abated, the operational expense (energy penalty) may be higher, the system may fail shortly after installation, and/or the radon level may increase. If any of these problems should occur, then the effort and funds expended for the task would be wasted. Note that, in some large buildings, a combination of approaches (active and passive) may be needed for successful mitigation (e.g., HVAC adjustment with SSD or ERV with passive sealing). To assist in the selection process, EPA recommends that a series of scientific tests, called mitigation diagnostics, be performed (EPA March 1994, 402-R-94-009). These diagnostics gather technical information on the characteristics of the building, which can then be used to determine the most appropriate mitigation means for the building.

In general, and for all practical purposes, mitigation diagnostics for family housing and large buildings are essentially the same. The list of typical diagnostics includes but is not limited to the following:

- Room-to-room distribution of radon levels: A comparison of the radon results collected within a nonresidential building against the building plans is made to determine if certain structural or mechanical components are possibly enhancing the radon levels within the building (Section 5.1.2).
    - Used to determine if more detailed HVAC or mechanical inspections are needed.
- Radon entry pathway: A specially configured continuous radon monitor (CRM) is used to locate entry points in the floor or walls of the building (Section 5.1.3).
    - Used to identify significant radon entry pathways for passive sealing.
- Air change: An instrument is used to monitor the loss rate of an inert tracer gas within a room or building (Section 5.1.4).
    - Used to determine the size of an ERV or the capacity of a SAM mitigation system or to calculate the makeup air volume needed for the HVAC system.
- Building shell leakage (also known as building envelope leakage): A blower door is used to generate a plot of shell pressure vs. intake air volume (Section 5.1.5).
    - Used to determine the volume of air required for SP mitigation.
- Building envelope differential pressure: A micromanometer is used to measure the pressure difference of the building relative to the outdoors (Section 5.1.6).
    - Used to determine if mechanical system adjustments/replacements are required.
- Subslab pressure field: An artificial vacuum field is induced under the floor to measure the lateral field extension (LFE) through a series of small holes drilled into

the floor. Concurrent with this measurement, a subslab permeability measurement can also be made to ensure proper fan selection (Section 5.1.8)

- Continuous radon monitor: A specially designed instrument performs hourly radon measurements. CRMs typically are used to perform short-term measurements in lieu of using passive detectors (Section 3.4.1). In diagnostics, CRMs are used to determine the causes of and effects on radon levels within buildings (e.g., the impact on radon levels during normal operation or after the adjustment of various building mechanical systems).

For buildings with HVACs, mechanical systems diagnostics would also include:

- HVAC inspection: A detailed review of all building mechanical drawings is followed by an inspection of all mechanical components.
  - Particular attention should be paid to any changes/modifications made to equipment or deviations from the original design operational parameters.
- Mechanical balance: A specialized instrument (i.e., flow hood, hot wire anemometer, or pitot tube) is used to measure the supply and return air and exhaust volumes throughout the building.
- Room-to- room differential pressure: A micromanometer is used to map room-to-room and differential pressure relative to the outdoors (Section 5.1.6).
- If present, the evaluation of the impact of energy setbacks during non-occupied hours

Table 11 summarizes typical mitigation diagnostics performed and the mitigation strategies that rely on the subject mitigation diagnostics to determine the best mitigation method in all types of buildings. Qualifications for contractors to perform these diagnostics are listed in the NAVRAMP Guidebook Section 4.2.9.

Table 11. Mitigation diagnostic summary

Diagnostic test	Description	Mitigation method
Radon entry pathway	Performs continuous radon measurements in suspected entry pathways	Passive sealing
Air change	Measures the air turnover rate of the unit	Energy recovery ventilation, supplemental air mitigation
Shell leakage	Determines the quantity of outdoor air required to pressurize the building to 4 Pa	Shell pressurization
Subslab diagnostic and permeability measurements	Quantifies the amount of vacuum required to adequately evacuate the subslab. Assists in the selection of suction point locations and fan size	Subslab depressurization
Differential pressure	Measures the differential pressure across the building shell relative to the outside	Passive mitigation via balancing of existing mechanical systems
Mechanical balance	Quantifies the volume of air being supplied or discharged at a mechanical register	Passive mitigation via balancing of existing mechanical systems

5.1.1 Pre-Mitigation Diagnostic Survey

At installations where there is a high probability that elevated radon will be detected [e.g., installation is in an EPA Zone 1, 2 or equivalent, RPC 1 designation) consideration may be given (not mandatory) to include the option of a pre-mitigation diagnostic survey in the testing contract. Contracting radon mitigation services can be complicated by structural, technical, access or logistical issues. Knowing these issues beforehand and addressing them in the mitigation contract will make radon mitigation implementation more predictable from a planning, scheduling, implementation and cost perspective. The best approach is a phased one where mitigation diagnostics are performed first with mitigation system designs provided. These findings and designs can then be incorporated into the mitigation bid package allowing for mitigation installation with fewer surprises. However, knowing which specific diagnostics measurements to contract for (Section 5.1) can be a challenge for those not familiar with radon mitigation. A review of the building plans followed by a walk-through inspection performed by a radon mitigation analyst (NAVRAMP Guidebook Section 4.2.9) can in most cases determine the best mitigation approaches for a particular room or building and make specific recommendations for mitigation diagnostics. With respect to timing, it would be best to perform this task between the issue of the testing report and the final project report. The rationale being that the findings of this survey could then be incorporated into the final testing project report.

As a minimum, the following information should be collected and/or reviewed:

- Confirm that all occupied or readily occupiable rooms have been tested within the building.
- Confirm the location of the room(s) with elevated radon levels and record them on an up-to-date floorplan.
- Confirm that the measurement location was in accordance with NAVRAMP guidelines.
- Measure the building shell pressure relative to the outdoors and verify that the rooms with elevated radon levels are not under negative pressure relative to the outdoors.
    - Determine if applicable which mechanical diagnostic are required.
- Determine if the building HVAC has any unoccupied period energy savings setbacks (See Section 4.3.7).
    - If present, determine if CRM diagnostic measurements should be performed.
- Review the building foundation plans to determine if any grade beams or other subslab structural components are present.
- Based upon the building design, determine if subslab depressurization (SSD) mitigation could be installed.
    - Determine if SSD diagnostics are required for the entire building or just the rooms with elevated radon levels.
    - Document the floor covering in the rooms most likely to have diagnostics performed.
    - Propose most likely suction point/system locations.
    - Determine if excavation would be required and the type of ground cover (e.g., grass, concrete, asphalt etc.).
- Determine, if possible, if radon entry pathways are present.
    - If present, perform radon entry pathway measurements if needed.
- Take photos of the building exterior and all other points of interest or concern.

5.1.2 Nonresidential Radon Test Data Diagnostics

In nonresidential buildings, the first diagnostic usually performed (EPA April 1994, 402-R-94-008) is a close examination of the building radon data vs. the building plans (i.e., floor, foundation, HVAC, and structural plans). Generally speaking, buildings with multiple rooms with elevated radon levels fall into one of the following categories (Figure 37):

- random—no discernable pattern
- uniform—all rooms are about the same
- linear—all the elevated rooms are aligned
- clustered—all the elevated rooms are in the same area of the building
- combinations of the four patterns in exceptionally large buildings.

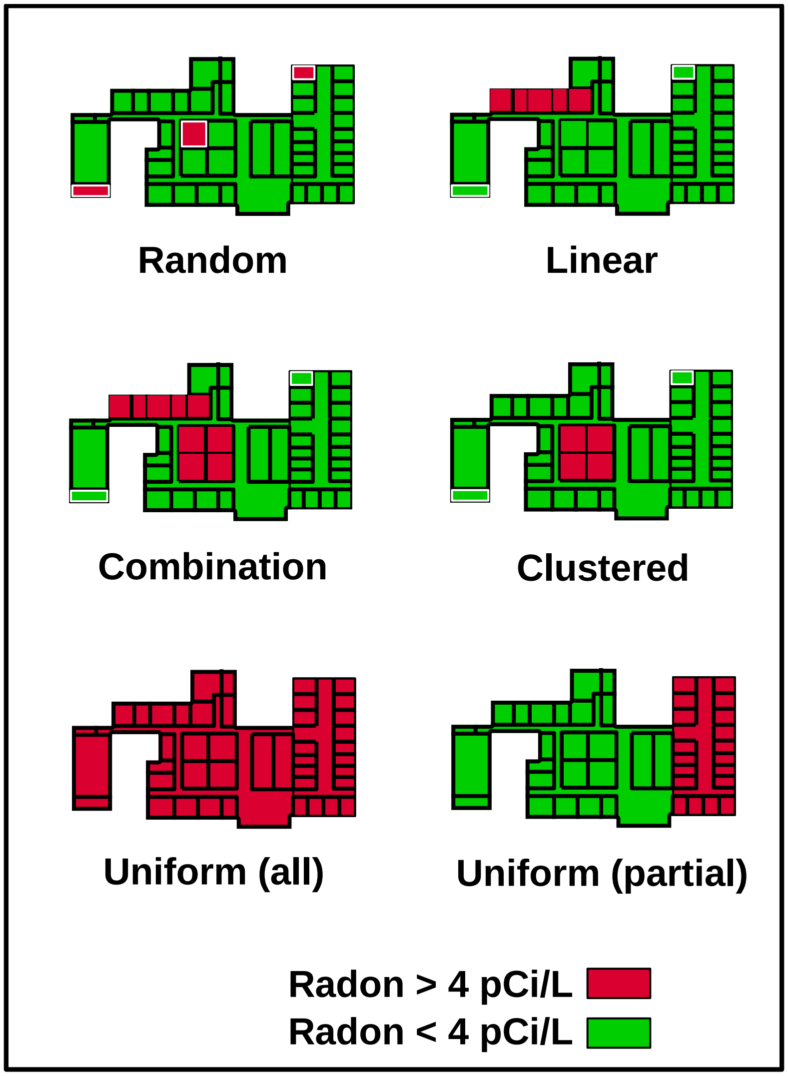
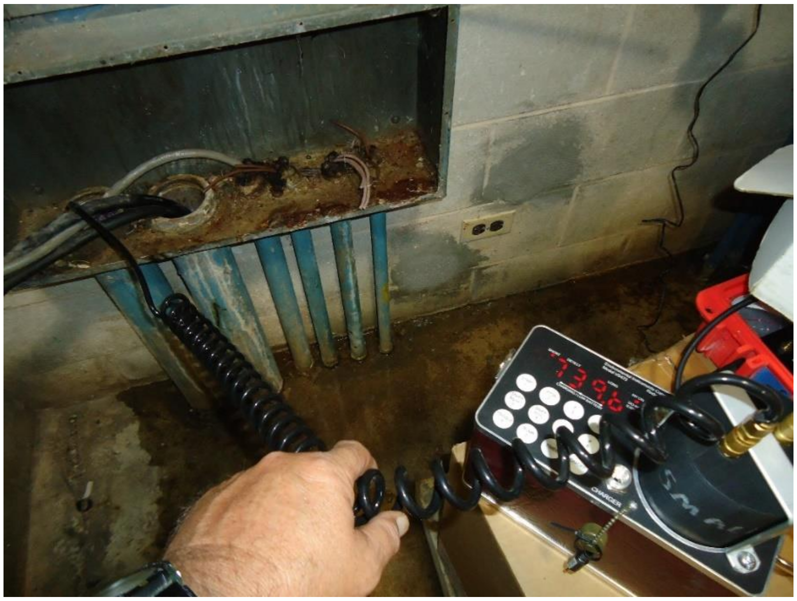


Figure 37. Distribution patterns of elevated radon levels in nonresidential buildings.

Analysis of historical data has shown that certain types of patterns indicate potential problems in a nonresidential building. For example, a uniform pattern in which all the rooms in the building or within a certain area of the building are at or near the same concentration indicates that the radon is being mined and distributed evenly by the building's mechanical system. This typically indicates an entry pathway that is common to all the rooms (e.g., expansion joints) or mining in the mechanical room. However, a uniform pattern with highly variable elevated radon levels may indicate a point source (typically the highest result) that is being mined and distributed. Linear or clustered patterns tend to indicate rooms with localized, substandard ventilation or a possible expansion joint or opening in the slab. Therefore, during the diagnostics phase, all the building mechanical components (HVAC and exhausts) should be closely examined. The examination should include a detailed review of the building mechanical drawings followed by a detailed inspection to confirm that the plans are current and accurate (review and inspection should be performed by a qualified HVAC engineer).

5.1.3 Radon Entry Pathway Diagnostic

Using a specially configured CRM, suspected radon entry pathway (e.g., cracks, expansion joints, open electrical or communication conduits) into the room are measured for radon. If identified, these pathways typically are passively sealed with caulk, expansion foam, or duct putty. To perform the measurement, the instrument intake tube is inserted into the suspected pathway (Picture 22). Typically, each measurement (under NAVRAMP, these measurements are considered diagnostic in nature and nonreportable) takes about 1–5 minutes to perform. A possible entry pathway for sealing is any result >5 times the room's current radon level. In Picture 22, the room was at 10 pCi/L. The instrument detected 739.6 pCi/L, and the conduit was sealed with duct putty (Picture 23).



Picture 22. Radon entry pathway measurement.

Picture 23. Passive sealing of a radon entry pathway

5.1.4 Air Change Diagnostic Measurement

A tracer gas (carbon dioxide or sulfur hexafluoride) is injected into the room and its decay is monitored by a specially configured instrument (Picture 24). The rate at which tracer gas disappears as a function of time is the ACH. A calculation involving the room volume and ACH is then performed to estimate the capacity of the ERV or SAM (EPA 1988, 625/5-87/019).

Picture 24. Air exchange instrument

5.1.5 Building Shell Leakage Diagnostic Measurement

To perform a shell leakage measurement, a blower door apparatus is used (Pictures 25 and 26). A blower door is a device used to pressurize or depressurize a building or room to determine the leakage characteristics of the building envelope. A variable-speed fan is temporarily mounted in a membrane-covered doorway or other opening to pressurize (or depressurize) the building or room by specified amounts. The flow rate through a calibrated orifice in the fan is measured at the different house pressures. The relationship between flow rate and pressure difference is an indication of shell or building envelope airtightness. The results are then plotted, and the curve extrapolated to estimate the air flow needed to achieve 4–8 Pa positive shell pressure. This value is the outdoor air volume needed for SP mitigation.

Within buildings that are operating under significant negative shell pressure (≤10 Pa) the blower door diagnostic can also be used to measure the required fresh air intake volume to achieve various building pressures. Since the blower door is a calibrated, adjustable air volume apparatus, simply adjusting the fan speed to achieve the desired shell pressures (typically 0 Pa, 4 Pa and 8 Pa are measured) will provide the needed volumes of outdoor air.

Picture 25. Front side of a blower door apparatus.

Picture 26. Back side of a blower door apparatus.

5.1.6 Building Envelope and Room-to-Room Differential Pressure

To measure a building's differential pressure (DP) relative to the outdoors, a micromanometer (Picture 27) with <1 Pa sensitivity (249.1 Pa = 1 in. WC) is used. The tubing from the reference port is inserted through a crack in a window or door and the DP is displayed on the readout. For best results, the measurement should be performed through openings on all sides of the building and averaged. In addition, the measurement should not be performed during periods of windy conditions. Relatively speaking, this measurement does not take long, is very simple to perform, and uses the same instrument used to perform SSD diagnostics (Section 5.1.8). Therefore, it is recommended that it be performed concurrently with nonresidential SSD diagnostic measurements and after SSD installation. The reason is that one of the leading causes of SSD mitigation failure in nonresidential buildings is the building developing a more negative shell pressure over time. If the design shell pressure is known, the time required to diagnose the failure and possibly accelerate mitigation restoration will be considerably less.

In family housing, particularly units with energy-efficient building envelopes, the measurement of the shell pressure should also include the cycling on and off of all the building exhaust systems (e.g., range hoods, bathroom fans, clothes dryers) individually and in combination.

In nonresidential buildings, room-to-room DP measurements are performed to identify any significant pressure imbalances in the building. In this diagnostic, a reference room (entrance lobby or central hallway are the most typical) is selected and the DP measured relative to the outdoors. All other rooms in the building are then measured relative to the reference pressure. Typically, these results are compared with the individual room radon results to determine if there is a correlation between individual room DPs and radon levels in particular rooms. If a correlation is found, it usually indicates a supply/exhaust imbalance, which may need to be corrected as part of the overall mitigation solution.

Picture 27. Typical micromanometer.

5.1.7 Flow Hood Diagnostics

A flow hood is a device that measures the supply or return air flow rate into or out of a ducted register during normal air handler operation (Picture 28). The flow hood channels the air through a short fabric duct to measure the flow of air entering or exiting the ducted register. Typically, the flow hood measurement is performed on all ducted registers in the building and other fan exhausts (e.g., kitchen, bathroom). The recorded measurements are then compared with the values listed in the building mechanical drawings. Any significant differences (±15% of the specified value) may need to be corrected as part of the overall mitigation of the building.

These measurements are also useful in estimating supply duct leakage. Simply sum the individual flow rates of each supply and subtract the sum of the individual return flow rates. The difference is the volume of supply air being lost in the duct work. Aside from the energy loss, significant losses of supply air tend to create ventilation and sometimes negative pressure issues within rooms towards the terminus of the supply duct. This in turn can increase the radon flux in the room and concentrate it because of the low ventilation rate. As unlikely as it may sound, some buildings have been mitigated with duct tape repairs on deteriorated supply duct joints.

Picture 28. Typical flow hood instrument.

5.1.8 Subslab Diagnostic Measurements

Knowing the radius of the LFE is an integral part of the design of an SSD system. In general, for an SSD system to be successful, the system pressure field (or, more precisely, the vacuum field) should cover at least 75% of the subslab surface area. At coverage less than this, the probability of a successful mitigation decreases. However, if the LFE is known before mitigation, the number of suction points, their locations, and the vacuum requirements for the SSD fan are easily determined.

To measure the LFE, a pressure field extension test (PFET) is performed. To conduct a PFET, a 1.5 in. to 3 in. diagnostic hole is drilled through the slab at a possible SSD suction point (this can be on the inside or outside of the building). One to ten perimeter field extension holes (3/8 in.) are then drilled at varying distances (1 to 20 ft) from the 1.5 in. to 3 in. diagnostic hole. With the use of a variable-speed, wet/dry vacuum cleaner or a specially adapted exhaust blower, a constant vacuum is applied across the slab (typical vacuums, depending on subslab conditions, are 500 Pa, 1000 Pa, or 5000 Pa). Using a micromanometer, the quantity of vacuum (Pa) present beneath the slab is then measured in the 3/8-in. extension holes. The extent of the vacuum field is then plotted on the building floor plan as a function of distance from the 1.5 in. to 3 in. diagnostic hole. To fully quantify the extent of the LFE, between 4 and 20 extension holes are usually required. Ideally, the depressurization field should extend concentrically beneath the slab around the 1.5 in. to 3 in. diagnostic hole, with the LFE limits being defined as areas of the slab with less than 2 to 5 Pa of vacuum. The distance in feet from the diagnostic hole to the 2 to 5 Pa line is the LFE radius. In large buildings, in particular where more than one room has elevated radon levels, more than one 1.5 in. to 3 in. diagnostic hole may be needed (Figure 38). However, family housing typically only requires one 1.5 in. to 3 in. diagnostic hole (Figure 39).

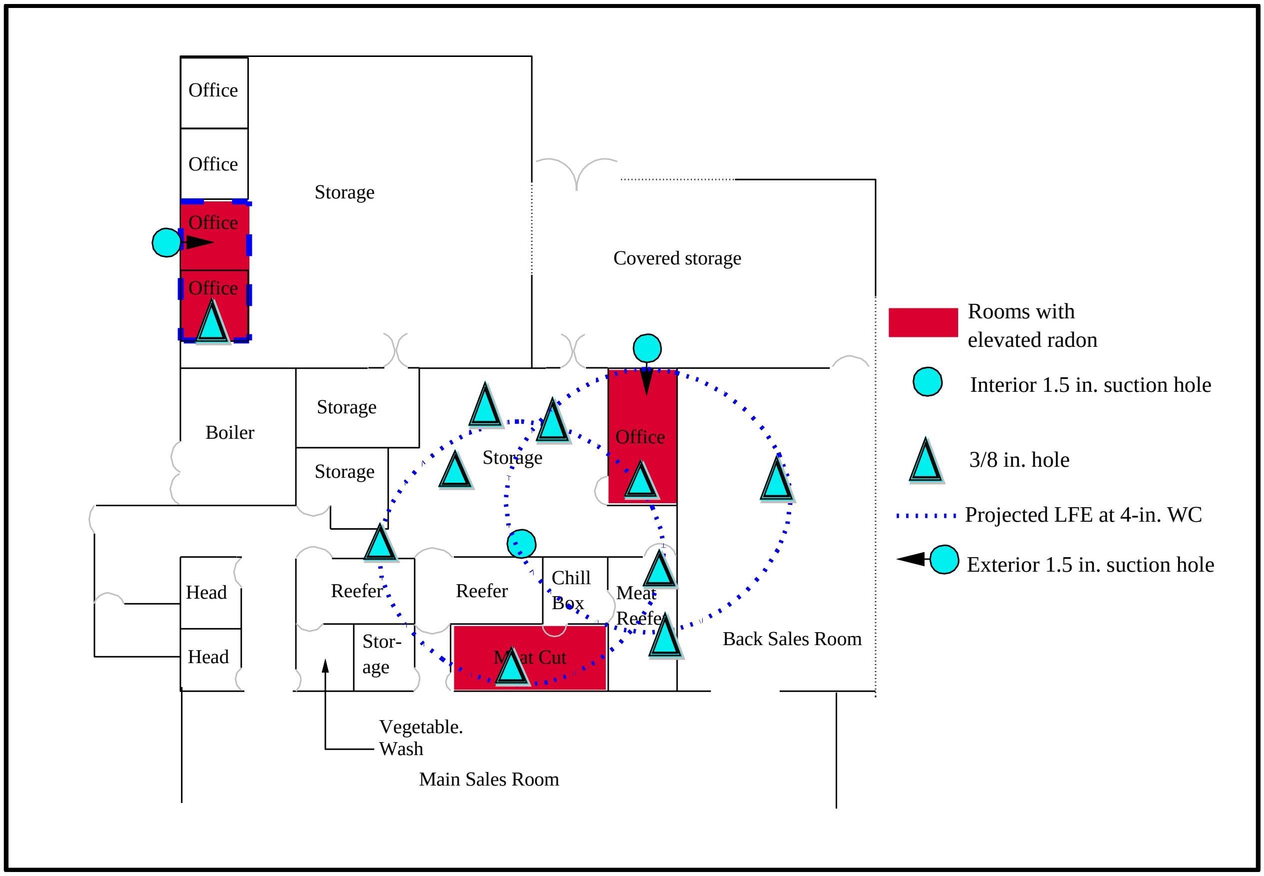


Figure 38. Example of an LFE diagnostic pattern in a large building.

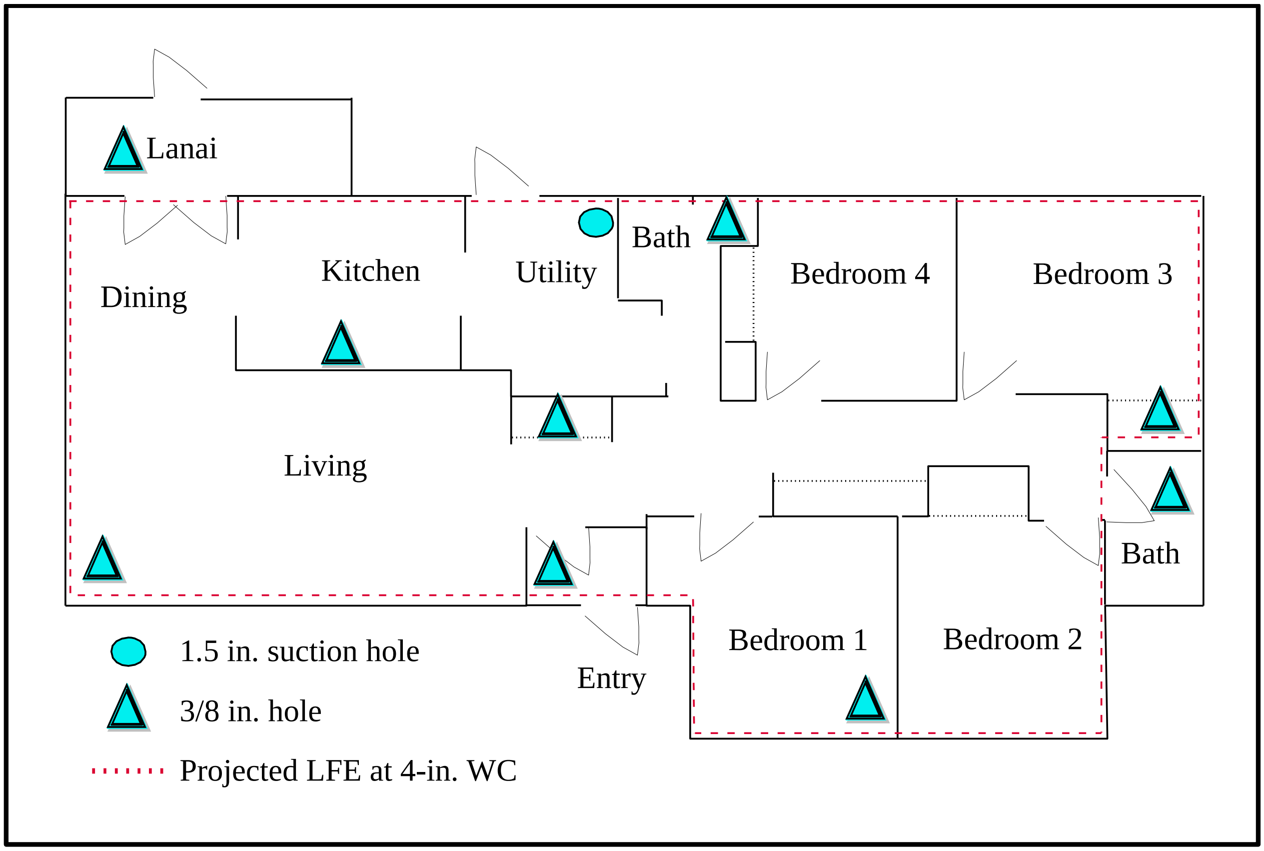


Figure 39. Example of a LFE diagnostic in family housing.

If the subslab has permeable gravel and no subslab obstructions, a typical LFE pattern would be similar to Figure 40. In this example, only one SSD would be required. However, subslab obstructions such as interior footers can prevent the vacuum from reaching all areas of the slab (note 0 Pa in lower right room in Figure 41). If obstructions are encountered, either an additional suction point or a jumper (Figure 42 A) is used. Essentially, a jumper is a tunnel through the slab and above the footer that allows the vacuum to extend into the enclosed area (Figure 42 B). However, if interior footers have good aggregate beneath them, then the vacuum field will not be impeded and could extend for a considerable distance (Figure 43). For nonresidential and bypass housing buildings, this sub-footer extension could result in achieving radon mitigation in one or more adjacent rooms or units.

If compact aggregate, compacted soil, or variable aggregate densities are present beneath the slab, then the LFE can become nonuniform or greatly reduced. Depending on the severity of LFE perturbation, the SSD system may become complicated, or the method may be eliminated as a mitigation option. In aggregates of varying densities, the vacuum gradient will bias toward the more permeable side (Figure 44). For this problem, a second suction point would be required in the non-evacuated portion of the slab. In cases with highly compacted aggregate or compacted coral, the LFE may not extend sufficiently for successful mitigation (Figure 45). However, in some cases, adding an additional suction point (Figure 46) or a more powerful fan will provide the needed coverage. The most difficult of all vacuum fields to work with is the “doughnut” field extension (Figure 47).

In this case, the aggregate around the building's foundation is loosely packed, but the center portion of the building has had its subslab fill compacted. This results in an elliptically shaped field extension pattern around the foundation but with no extension into the center of the subslab. However, mitigation can occur if the major radon source term is located in the more permeable foundation aggregate. If it is not, then radon reduction will not be complete. Note that it is not unusual for a large or complex subslab to have more than one LFE pattern. In these cases, each slab section is treated independently.

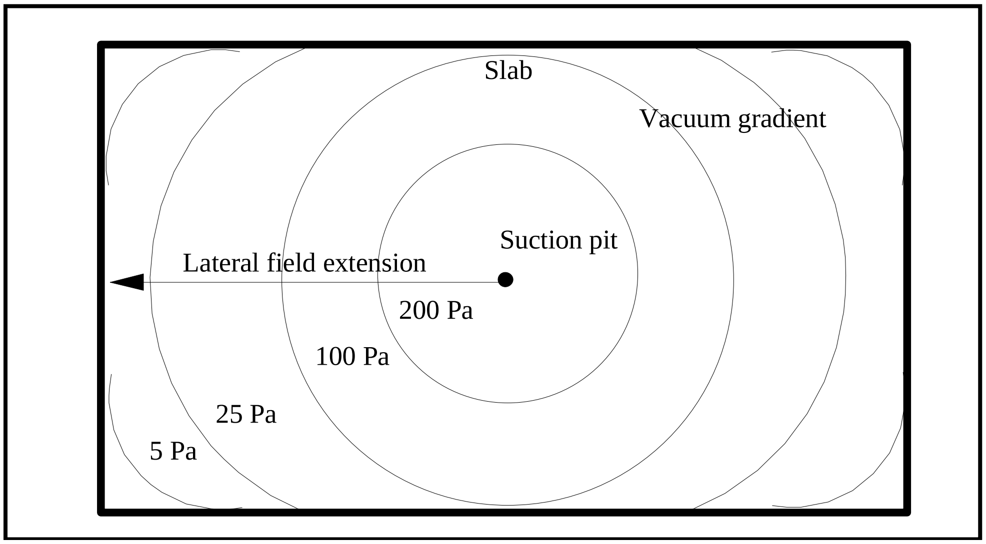


Figure 40. Uniform vacuum gradient under the slab.

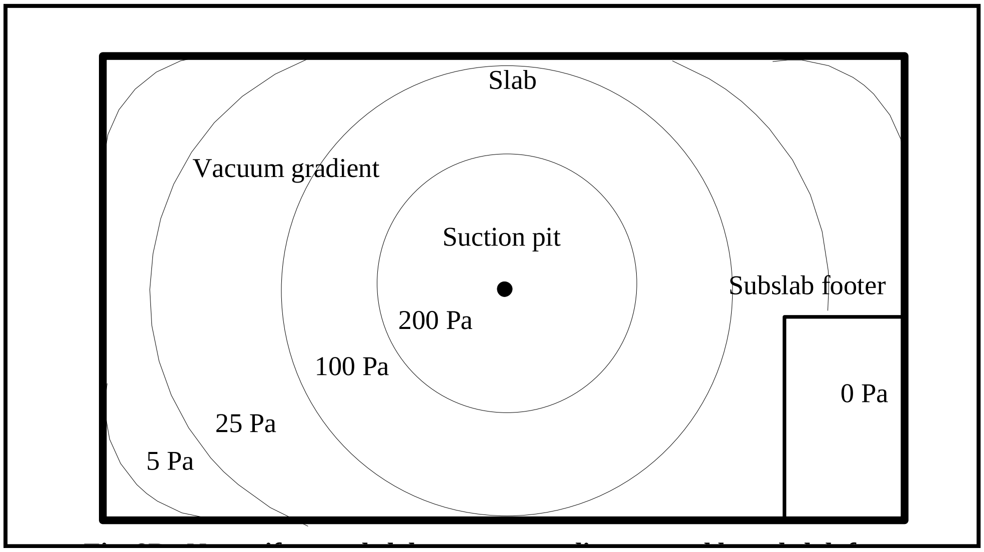


Figure 41. Non-uniform vacuum gradients.

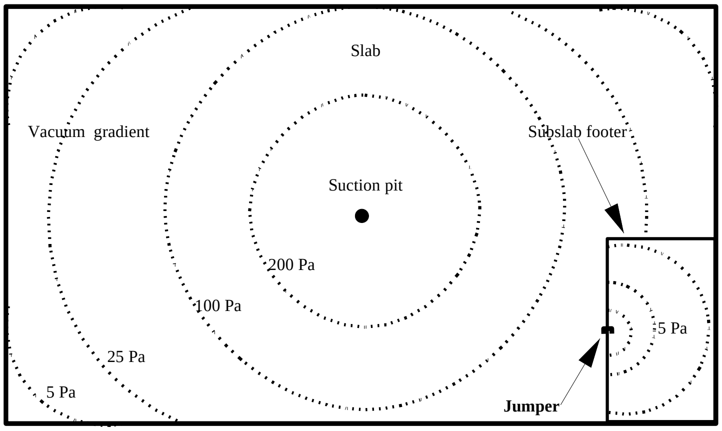


Fig. A. Increased field extension with jumper

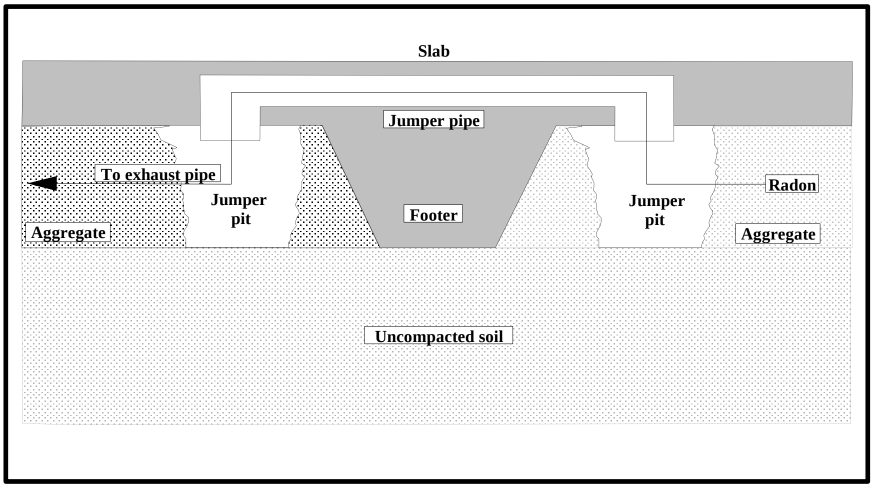


Fig. B. Cross-section of footer jumper

Figure 42. Subslab jumpers.

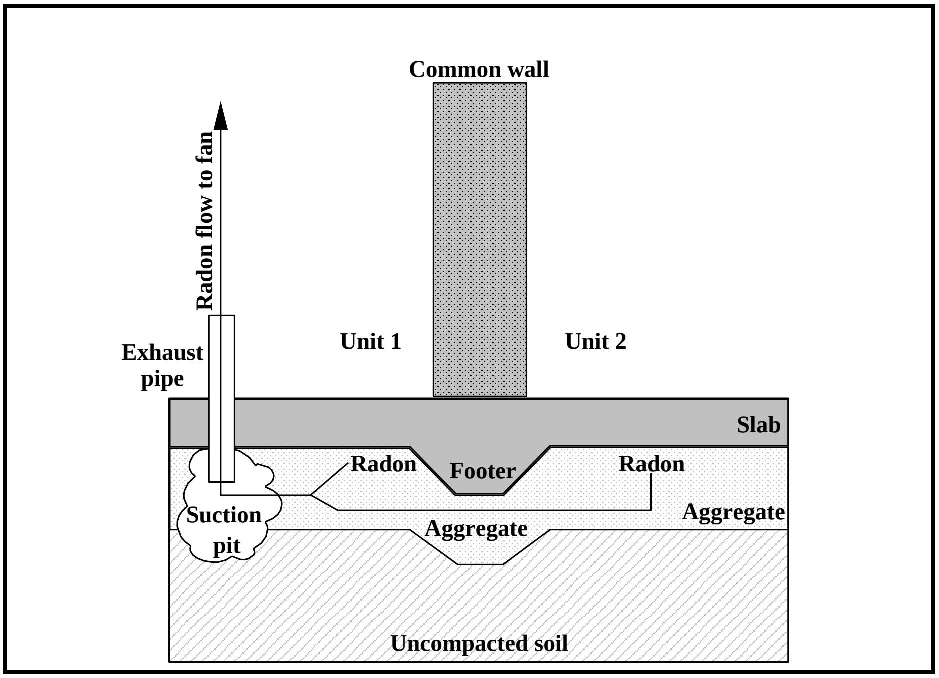


Figure 43. Vacuum extension under a footer

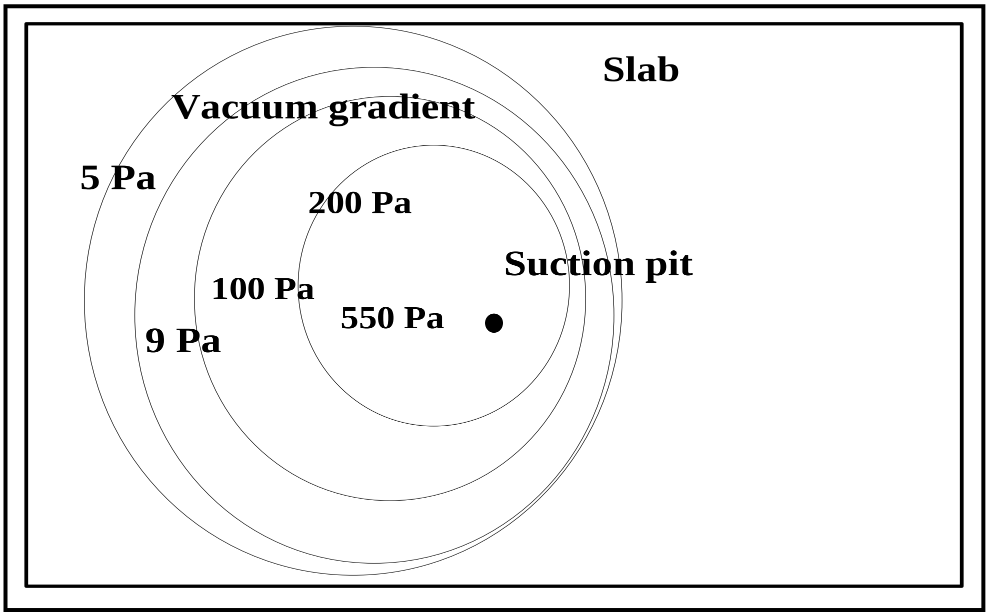


Figure 44. Biased, uniform subslab gradient.

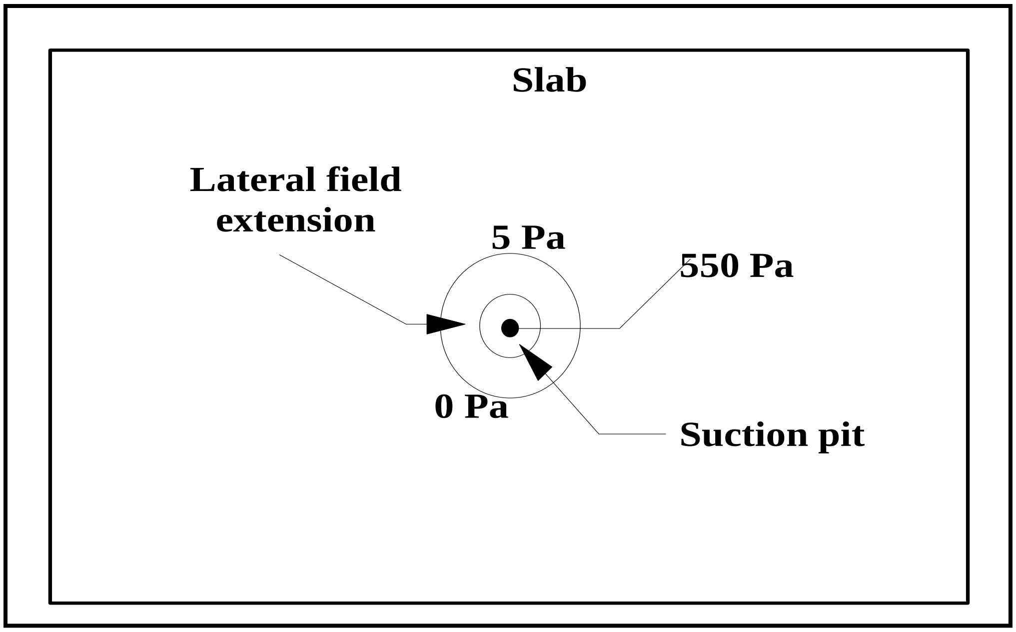


Figure 45. Lateral field extension in tight soils or aggregate.

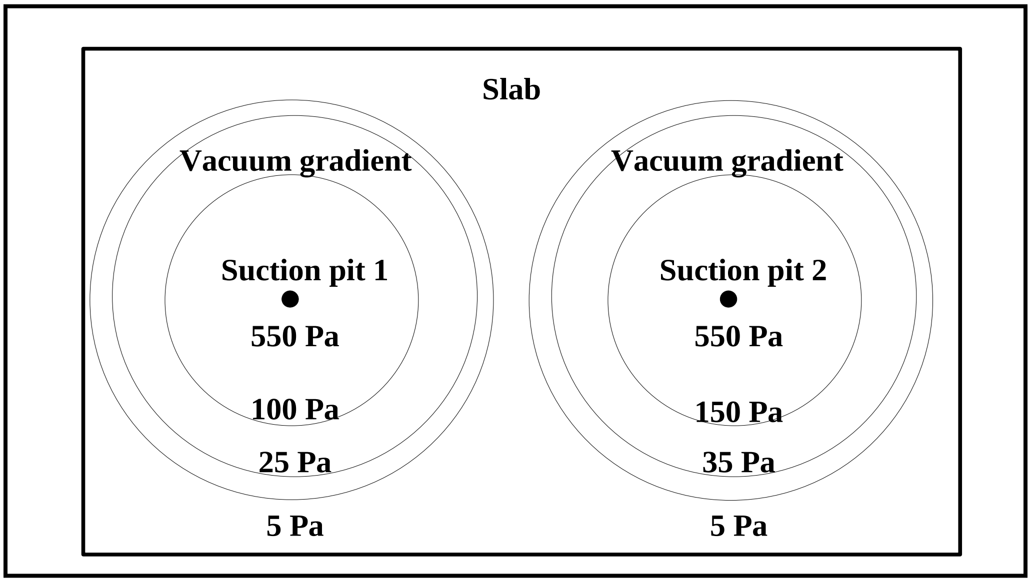


Figure 46. Uniform vacuum gradients in tight aggregate.

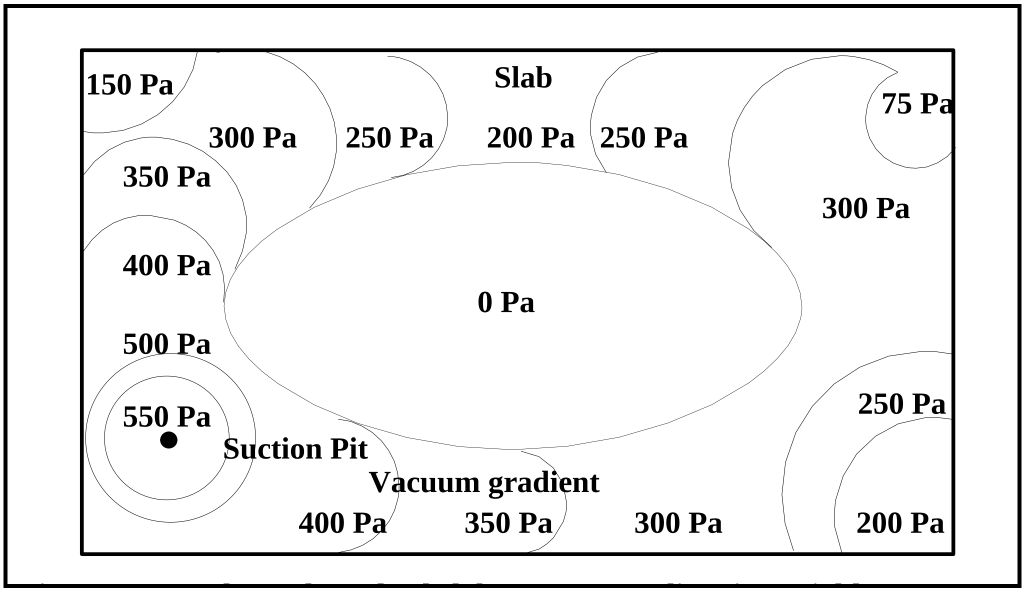


Figure 47. Doughnut-shaped vacuum gradient.

Once the LFE has been established, the appropriate size of SSD mitigation fan needs to be selected. In some cases, this can be determined audibly by simply listening to the shop vacuum when it is sucking air from under the floor. For example, a high-pitched whine is an indicator that a low-flow/high-suction fan will be required. A minimal auditable change indicates that a high-flow/low-suction fan is required. In some cases, a subslab permeability test (SPT) is performed (see discussion of fan selection in Section 5.1.8) to more finely tune the fan selection. Selecting the appropriate fan is an important aspect of SSD design. Fans that operate at or near their maximum vacuum capacity tend not to last as long as the same model fans operating at 30–80% of vacuum capacity. The reason is that all fans require a minimal air flow to cool the fan motor. If the flow drops below that threshold, the fan lifetime typically drops to <30% of the projected lifetime. However, for high-flow fans, the fan lifetime is not affected but electrical energy may be wasted. Therefore, the proper fan selection is critical for long-term continuous efficient operation. Fan manufacturers publish and provide fan performance curves (pressure vs. flow) that indicate minimal flow requirements at a given pressure.

An SPT measures the ease with which air moves through the aggregate/soil beneath the slab (i.e., flow for a given vacuum). This property of porous materials is permeability. To measure permeability beneath a slab, it is necessary to record the flows through a slab penetration. Using the LFE 1.5 in. to 3 in. diagnostic hole, an SPT measurement apparatus is inserted (Picture 29). By varying the speed of the vacuum cleaner, the flow required to produce a given pressure can be measured. An *x/y*-data plot of the data pairs can be used then to select the proper fan for the SSD system from the manufacturer flow curves. Figure 48 illustrates the most common radon mitigation fan performance curves (additional fan information is found in Sections 4.3.2.10 and 5.1.8). Note that air flow from the subslab will also be affected by the size of the radon vent pipe. Figure 49 illustrates the impact on air flow using a 3 in. vs. 4 in. vent pipe. Figure 50 shows soil resistance vs. fan performance.

Picture 29. Example of an SSD diagnostic wand.

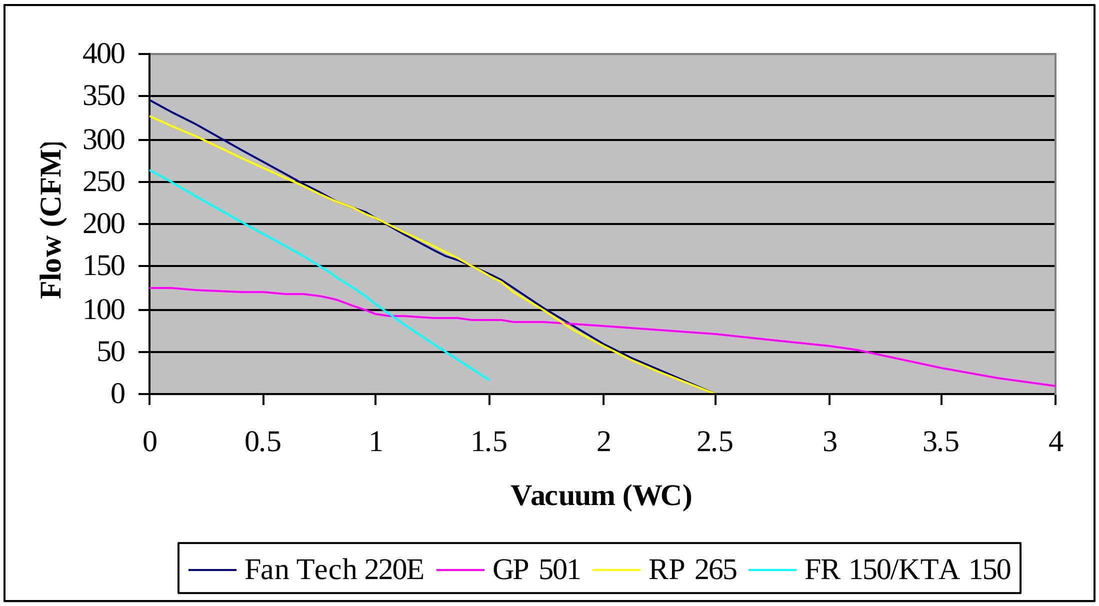


Figure 48. Typical manufactures subslab fan performance curves.

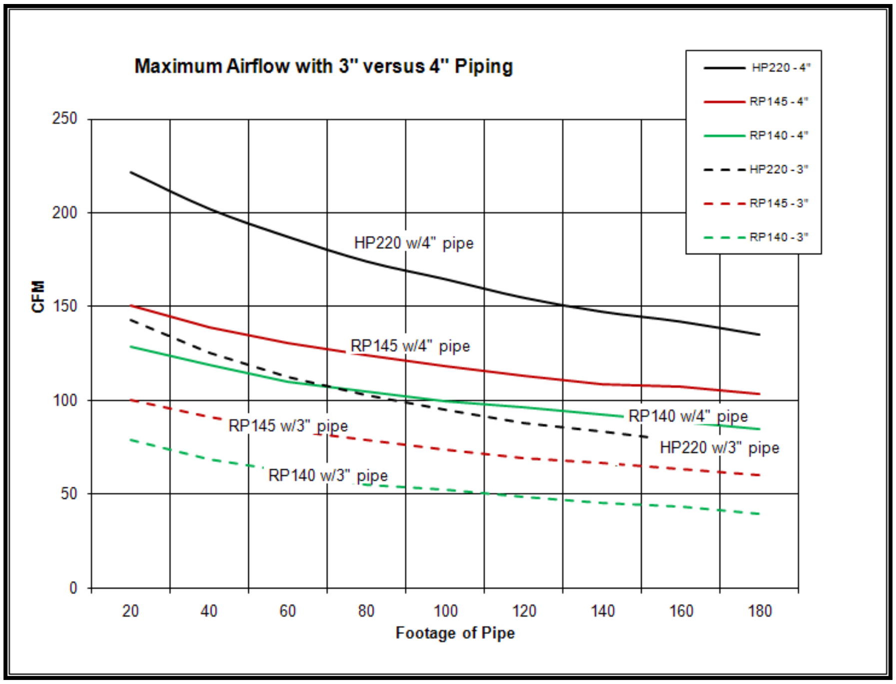


Figure 49. Fan performance curves using 3 in. or 4 in. vent pipe.

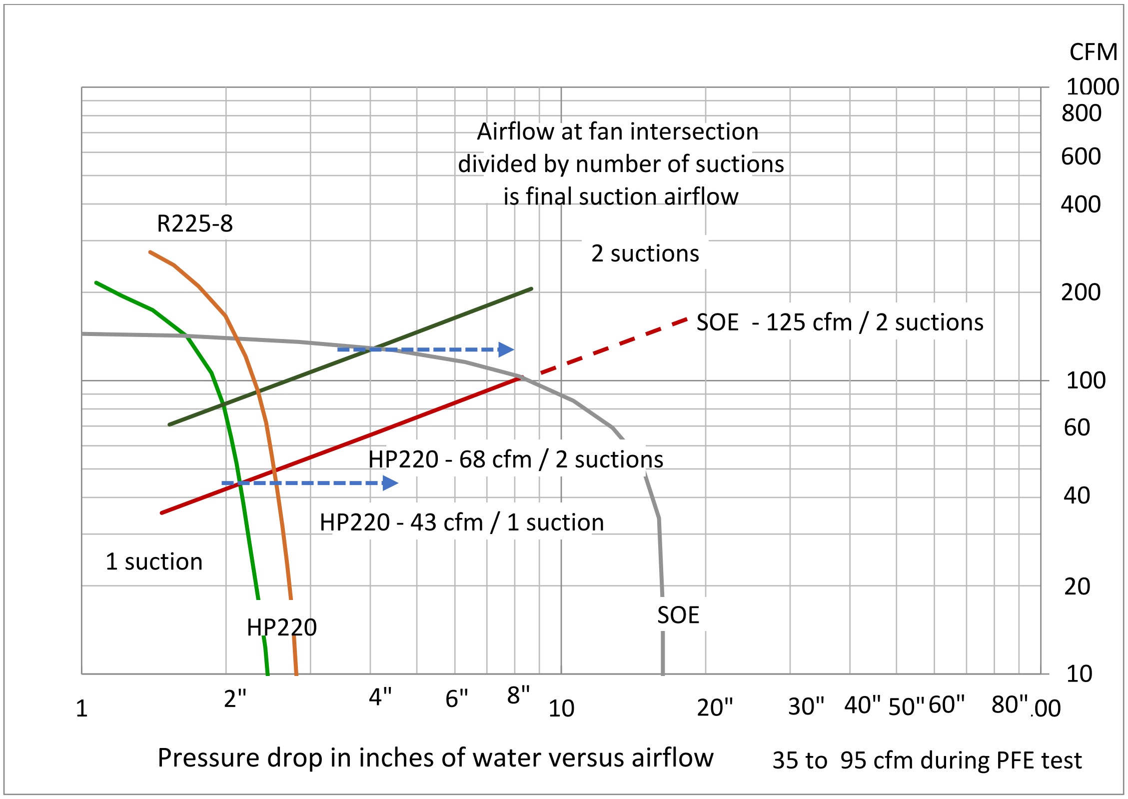


Figure 50. Typical soil resistance vs. fan performance plot.

For buildings equipped with RRNC vent piping, there is no need to drill the 1.5 in. to 3 in. diagnostic hole. To perform the diagnostic, an appropriately sized radon mitigation fan (consult building plans) is temporarily installed on the vent pipe exhaust. When the fan is activated, the fan pressure is measured in the pipe and a series of 3/8 in. holes are drilled within the rooms identified as having elevated radon levels to determine the RRNC LFE. If the vacuum measured is not enough or too much, the diagnostic is repeated with a different size of fan.

5.1.9 Continuous Radon Monitor Diagnostics

CRMs with their hourly resolution are a very powerful tool in radon measurement. However, a popular misconception is that they are the final word. Although CRMs are more accurate than passive detectors, they are a short-term measurement which is only representative of the measured time period, not the annual average. If a CRM measurement is significantly lower than the long-term or annual measurement, then there is high probability that the radon levels at other times or seasons are higher than the annual average. Therefore, in cases where the CRM measurement is < 4 pCi/L and the long-term or annual measurement is > 4 pCi/L to reach a defensible testing conclusion, multiple CRM measurements performed in other seasons would be required.

As was discussed in Section 3.4.1, pulse ion chamber and solid-state silicone chip CRMs rely on the diffusion of radon into the measurement chamber. Consequently, the radon levels in the room currently will be different from those currently in the measurement chamber. In other words, the radon level being currently reported may have actually occurred 1 to 3 h before. In order to perform cause and effect CRM diagnostics the lag time for the instrument being used must be known in order to better understand the event(s) in question. If the lag time is known, the time axis can be shifted the appropriate number of hours on the plot to provide a more representative plot for analysis.

Within most buildings within the Navy and USMC, CRM measurements are not needed to achieve the phase testing objectives. In addition, under NAVRAMP, confirmation tests are not required for a valid radon test result. Therefore, performing short-term CRM measurements in all family housing units and rooms at an installation identified as having radon levels ≥ 4 pCi/L is not needed. However, a close review of thousands of CRM measurements performed at naval installations has identified niche applications where CRM measurements may be helpful during mitigation diagnostics, in particular where a building's mechanicals are suspected as being a contributor to the elevated radon levels in the building.

In naval family housing the mechanical systems are pretty simple and straight forward. Most units have either a central forced air system (package, or split) or area mini-splits which provides heating, cooling and dehumidification. Typically, these units do not have fresh-air makeups. In most residential units, the conditioning cycle is intermittent controlled by a central thermostat. Exhaust systems are relatively low volume and are localized (bathroom, kitchen cook top, and clothes dryers) and typically turned on and off as needed by the occupant. Because of this simplicity, it is extremely rare to find a family housing unit whose elevated radon levels are caused by the building mechanicals.

Therefore, CRM measurements in family housing in most cases would not provide any added mitigation diagnostic benefit.

For nonresidential buildings the operation of the building's mechanicals can contribute to elevated radon levels being present. If a mechanical issue is causing elevated radon levels, it usually falls into one of the following categories: lack of fresh-air, localized imbalanced supply or returns, or excessive exhaust. In addition, certain types of energy saving features may enhance or reduce the radon levels during their operation. Correlating the cause and effect of the operational impact of the various building mechanical systems greatly assists with ultimate selection of a radon mitigation technique. In Figure 51 to save energy, the ERV (the only source of fresh-air for the building) was only activated when the CO_2 levels reached a certain concentration. When the levels lower limit was achieved, the ERV shut off. To further enhance energy savings, the ERV was also turned off nightly from 1900 until 0600 the next morning and all weekends and holidays. Although activation of the on-demand ERV did lower radon levels within the building, the levels were still ≥ 4 pCi/L during the work day. However, by leaving the ERV on 24/7 the radon levels were reduced and maintained to < 1 pCi/L with no measurable changes in temperature or humidly. After discussions with the energy conservation officer and the installation mechanical shop, it was decided that leaving the ERV on was the best radon mitigation option.

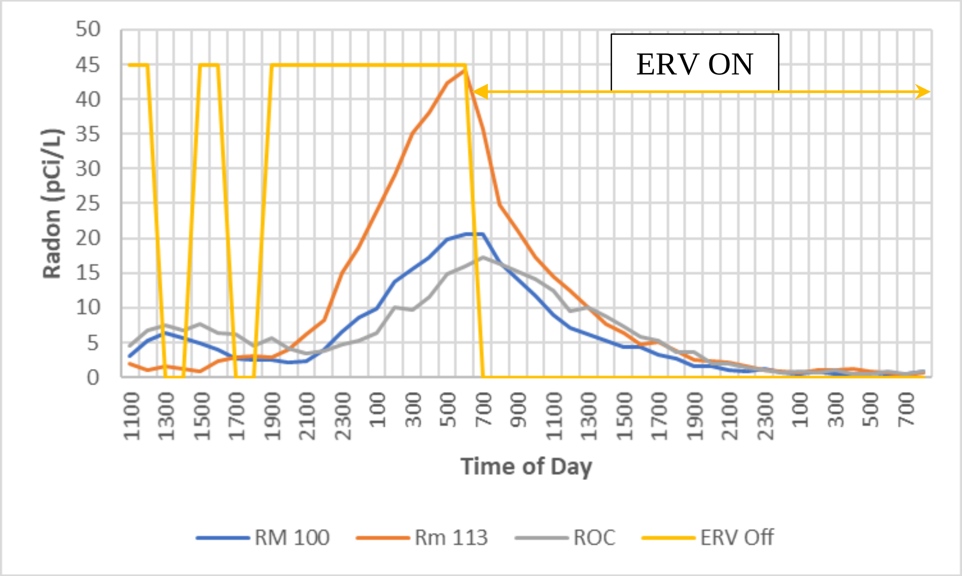


Figure 51. Example of a CRM plot where the ERV cycles on and off.

Another HVAC energy saving feature which can impact radon levels is an economizer. During the cooling season when outdoor temperature and humidity are within a specific range, the HVAC will draw in considerably more outdoor air and operate at a lower conditioning setting. This influx of fresh-air will dilute the radon levels in the building and in some cases pressurize the building shell as well. The frequency and duration of the economizer cycle is episodic and dependent on very specific indoor and outdoor conditions. Once the indoor conditions are met or exceeded, the fresh-air volume is reduced back to its minimal settings and normal conditioning operations resume. Figure 52 shows the impact of an economizer which both ventilates and pressurizes the building.

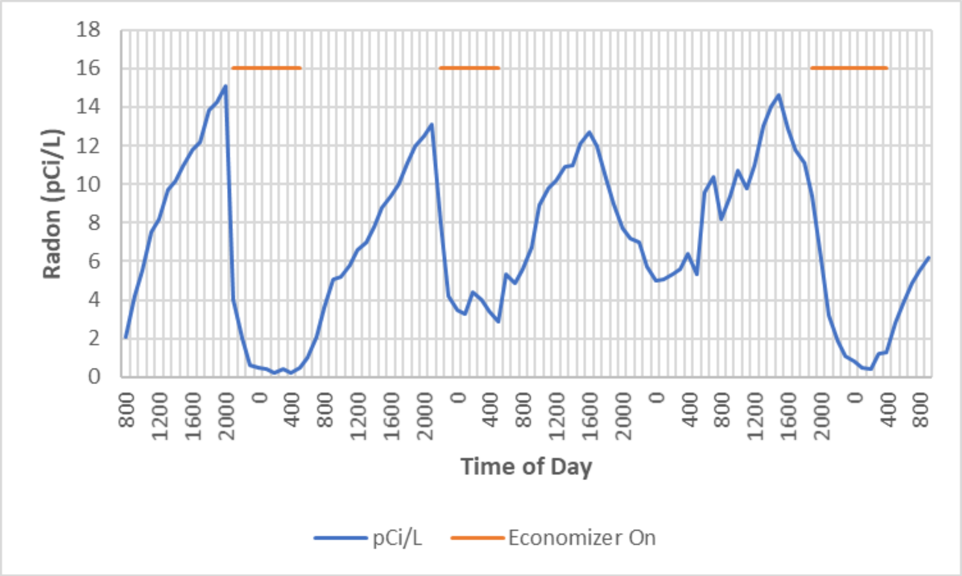


Figure 52. Impact of a HVAC economizer on indoor radon levels.

In some buildings, HVAC units are equipped with a timer which reduces or eliminates the intake of fresh-air during off hours and/or condition indoor air at a reduced capacity (typically referred to as energy set back). To maintain some ventilation, it is not unusual for these buildings to operate during these times with the exhaust blowers on. This absence of fresh-air with exhaust on can result in enhanced negative shell pressures which greatly increase the off-hour radon levels. In these buildings it is the radon level just prior to the activation of occupied HVAC settings that is most critical. With restoration of HVAC occupied settings, the radon levels typically drop. The rate and extent of decrease being dependent upon the occupied air exchange rate and shell pressure. For example, Figure 53 shows a nonresidential room (annual average radon level 12.9 pCi/L) with an energy Monday through Friday setback from 1900 through 0600. These settings were maintained over the weekend. As can be seen from the plot, the radon levels drop very quickly after the occupied HVAC settings are restored with radon levels dropping to < 4 pCi/L by 1000 on Tuesday through Friday (average occupied radon level 3.8 pCi/L). But, because of the buildup over the weekend, radon levels on Monday did not drop below 4 pCi/L until 1300 (average occupied radon level 7.4 pCi/L). Averaging the occupied radon levels for Monday through Friday finds the room at 4.5 pCi/L. Follow-up CRM measurements performed 6 months later (opposite season) found slightly higher radon levels but with an identical CRM pattern. The proposed mitigation solution was to reactivate the HVAC at 0200 Monday morning and reactivate one hour earlier (e.g., 0500) on Tuesday through Friday. Interestingly, consultation with the energy conservation officer revealed that the energy costs were higher than installing a single SSD mitigation system with a 45-watt fan.

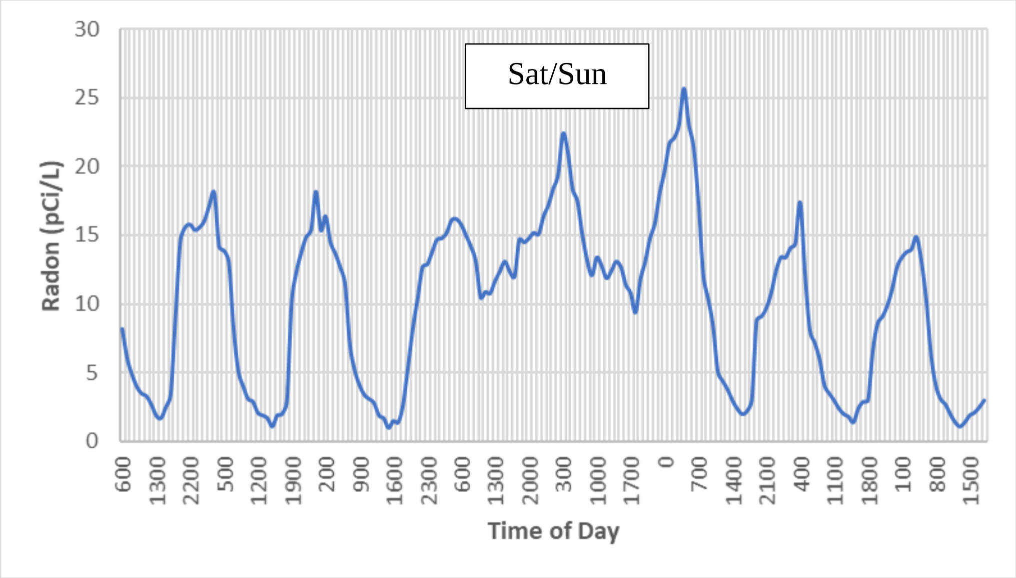


Figure 53. Unoccupied energy set back with including the weekend

In some cases, deactivation of the energy set back can appear to result in mitigation. In Figure 54 annual radon levels were found to be 5.9 pCi/L. CRM measurements performed with the energy set back on found radon levels at 4.9 pCi/L. During the occupied times, the radon levels averaged 3.6 pCi/L. To measure the impact of the energy set back, the CRM measurement was repeated immediately with the energy set back off. The findings (Figure 54) were that the radon levels during the occupied periods were virtually unchanged and the average result was now 3.5 pCi/L. Although it appeared that radon mitigation could be accomplished with the energy setback left permanently off, a 1-year test with the set back off found that the radon levels at 5.1 pCi/L.

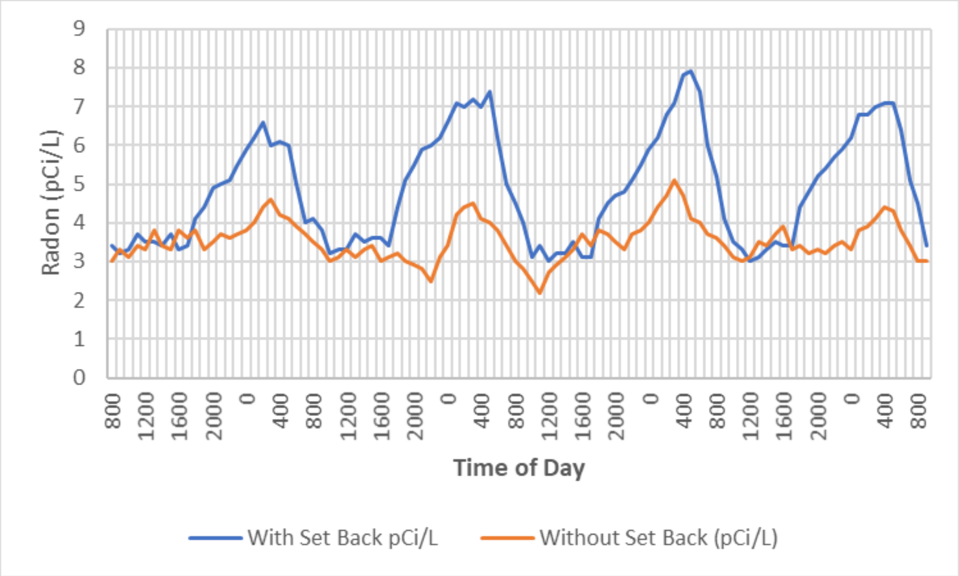


Figure 54. Energy set back on vs. off

A more complicated HVAC design to diagnose are those equipped with a fresh-air articulated feedback damper. These units come with a programable controller which can respond to CO_2, humidity and temperature and adjust the intake air volume accordingly. The CRM plot shown in Figure 55 was taken within a gym equipped with a CO_2 sensor (annual radon level 8.7 pCi/L). The sensor averaged the CO_2 levels over a 15-minute interval. If the CO_2 levels were < 900 ppm, the fresh-air volume remained unchanged (1000 ft^3/min). However, if CO_2 levels were ≥ 900 ppm the volume of fresh-air would double (2000 ft^3/min) and remain at that volume until the levels were reduced to < 700 ppm. During nonpeak occupancy times it was observed that the CO_2 levels rarely reached the 900-ppm threshold. During peak occupancy times (0500 to 0800, 1100-1300, and 1600-2000) it was not unusual to observe the increased fresh-air volume setting multiple times within a 1 to 2 h period. Figure 55 shows the correlation between building peak occupancy and reduced radon levels as a result of the increase in fresh-air volume. A closer look at the radon levels during the higher fresh-air volume period shows radon levels consistently below 4 pCi/L after 1-2 h of operation. It was then decided to simply set the minimum fresh-air volume to the same volume used in during the CO_2 reduction cycle. Although successful in keeping radon levels consistently < 4 pCi/L, within one week the humidity within the building went from 55% RH to 70% RH. Therefore, the original fresh-air settings had to be restored and another mitigation method used.

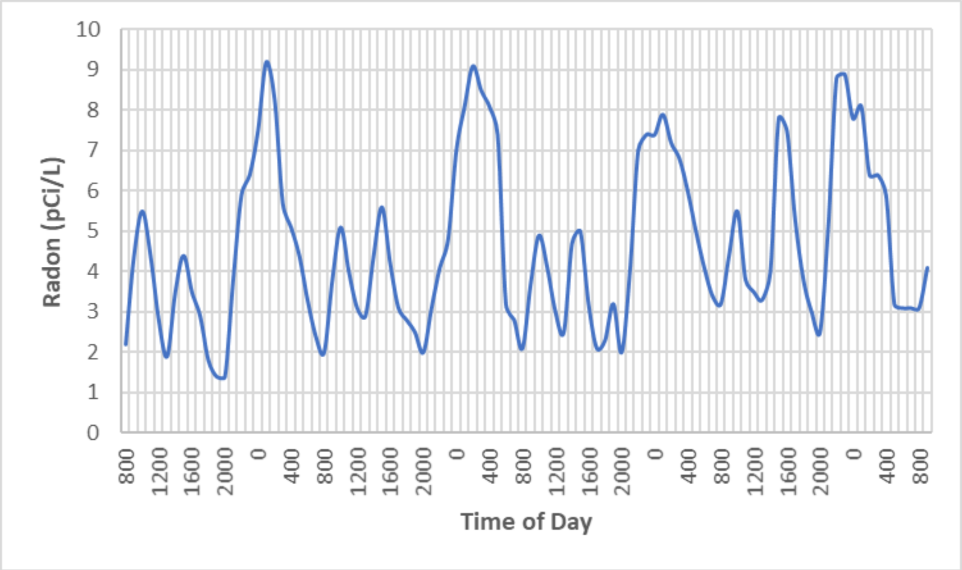


Figure 55. Impact of fresh-air intake with on-demand CO_2 sensor

At installations which undergo distinct seasons (e.g., winter, spring, summer and fall), the conclusion of a single CRM measurement can be biased towards the current seasonal HVAC settings. It is not unusual for a building to have a forced air AC system for summer and a hot water radiant heating system for winter. In addition, because of transition times from heating to cooling or vice versa there may be an extended time period in which the building is neither heated or cooled. However, in most cases the forced air system will still be operating with a reduced volume of fresh-air makeup. A good example of this is a building located in the northeast United States. One year radon testing found a room with 7.1 pCi/L. However, a CRM test performed in July found 2.2 pCi/L (Figure 56). Reperforming the CRM in January the following year found 8.2 pCi/L (Figure 57). Short-term testing (electret) during October and April found 4.1 pCi/L and 3.0 pCi/L respectively. An investigation into the wide range in radon concentration as a function of season found the following:

- From June to September forced air AC was on with fresh-air make up set to design specification (Figure 56)
- From November through March hot water radiant heat was on, forced air system was off, and the building had no fresh-air makeup (Figure 57)
- From April to May and October the forced air was on (cooling was off) but with a 75% reduced fresh-air volume relative to the design specification

Based upon these findings, a mechanical solution was ruled out and the building was mitigated using SSD.

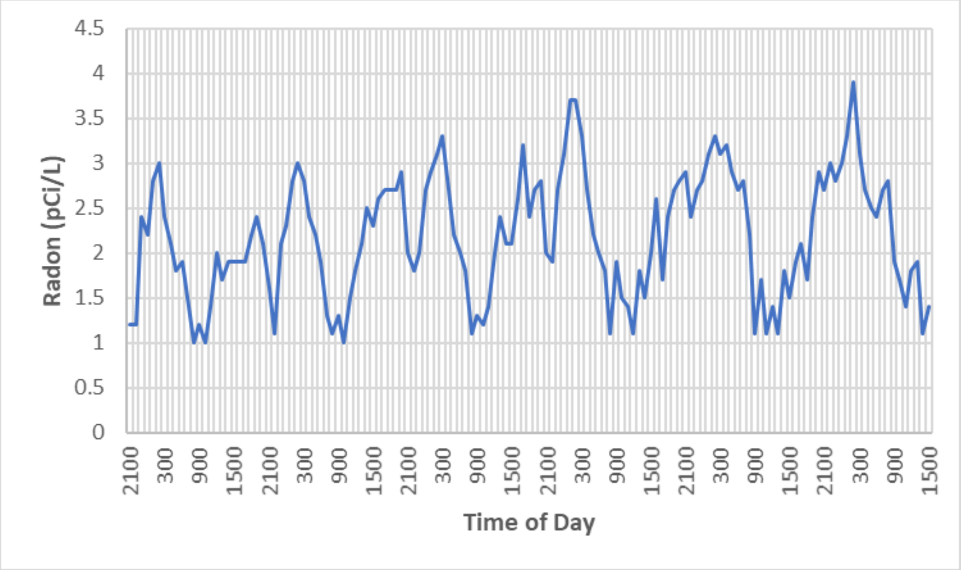


Figure 56. Cooling season forced air system on

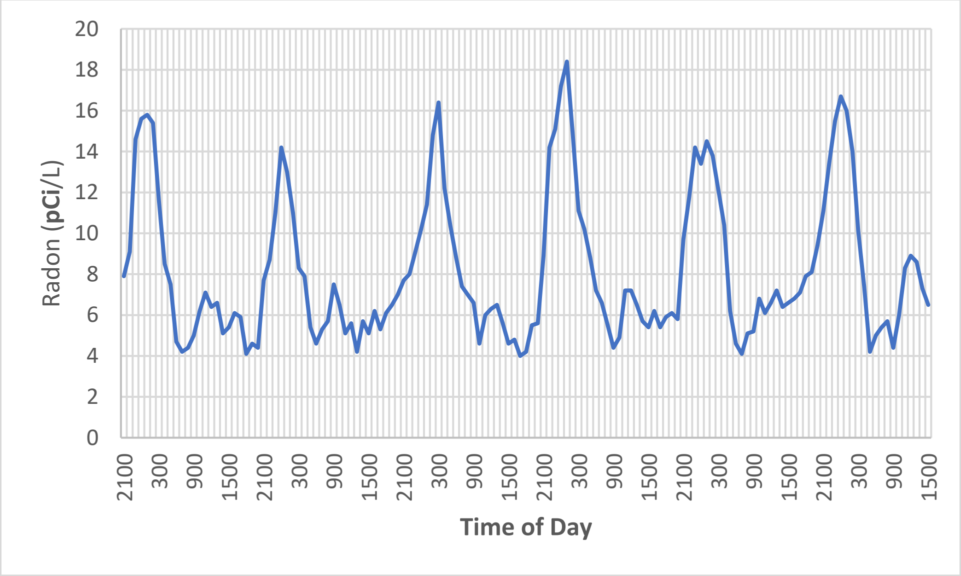


Figure 57. Radiant hot water heat with no forced air

The most common mechanical problem seen in Navy and USMC buildings is excessive building exhaust. In the example shown in Figure 58 a maintenance shop had 3 exhaust systems. The exhaust blowers were cycled on and off in different combinations to determine each one's contribution.

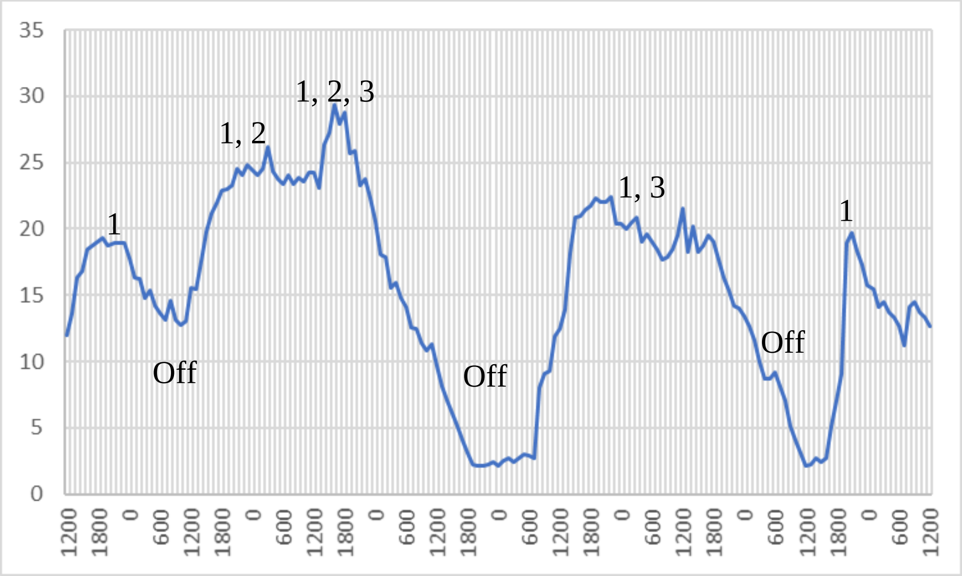


Figure 58. Impact of exhaust systems on indoor radon levels

A less common design feature in nonresidential HVACs is the placement of return air plenum under the slab. During blower operation a typical return air plenum can be between

(-) 30 to (-) 60 Pa. If the ductwork was not sealed properly or if it has deteriorated over time the vacuum will extend from the return into the surrounding aggregate bed. Typically, when this occurs, the room-to-room radon levels in that HVAC zone are fairly consistent. In addition, the CRM plot shows very consistent radon levels (Figure 59).

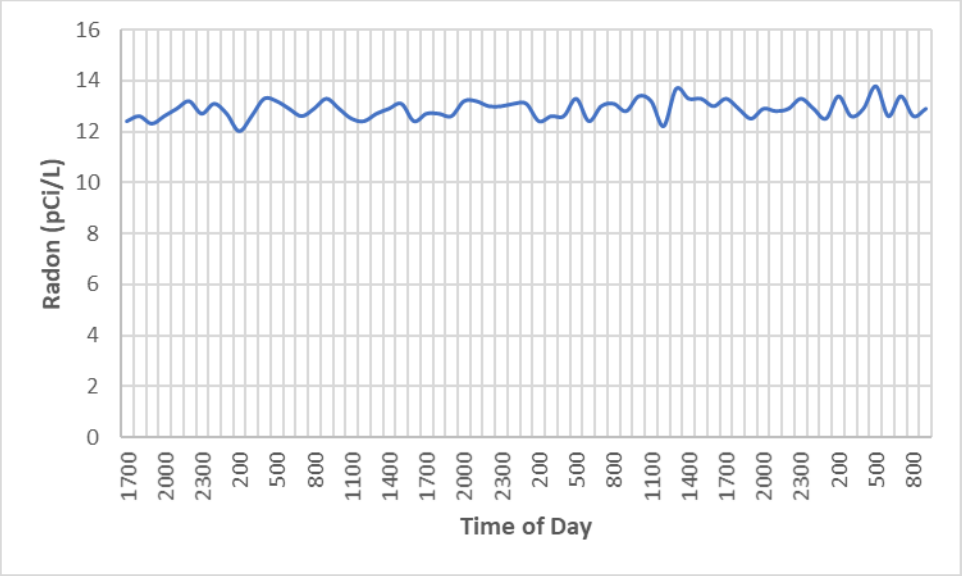


Figure 59. Radon levels with a subslab return

In summary, within buildings with potential mechanical issues, CRM measurements are an excellent tool when used as a cause-and-effect diagnostic. Notably, although more accurate than short-term passive detectors, a CRM measurement is still only a short-term measurement which is only representative of the radon levels during the measurement period, not for the entire year. Thus, multi-CRM measurements may be required throughout the year to gain a better understanding of the annual average.

5.2 FAMILY HOUSING MITIGATION DIAGNOSTICS APPROACHES

In selecting a mitigation approach for family housing, to the extent possible, it is highly recommended that the mitigation method, design, system location, and mitigation components be standardized for all family housing. For all practical purposes, radon mitigation systems, once installed, become a permanent addition to the housing unit. These systems will require periodic inspection, maintenance and repair. Standardizing the design can greatly reduce maintenance staff training and the variety of spare parts required, which in turn will save money in the long run. This consideration should factor heavily in the selection of mitigation diagnostics during the planning stages.

In family housing, in most cases, SSD mitigation diagnostics should be the first choice in housing units with slabs. If the SSD mitigation diagnostics determine that SSD mitigation is viable, no further diagnostics are usually needed. However, as circumstances dictate, radon entry pathway (Section 5.1.3) and building envelope DP measurements (Section 5.1.6) may also be required (typically, the need for these diagnostics is determined during the SSD diagnostic). These diagnostics typically only take 2–4 hours per unit to perform and can be performed with the resident present. Hearing protection will be required during the drilling parts of the diagnostics.

Shell leakage and air change measurements should be performed only in cases where SSD mitigation has been determined not to be viable. Examples of cases where SSD diagnostics would not be performed would include but not be limited to the following:

- Prior SSD mitigation diagnostics in a similar type of housing at the installation determined that SSD mitigation was not viable.
- Prior attempts at SSD mitigation in this type of family housing at the installation have been unsuccessful.
- The design of the building does not allow for SSD mitigation (e.g., mid or high-rise apartment buildings or historic preservation buildings).
- The interior and exterior layout of the unit does not allow for the installation of an SSD vent pipe.
- The unit has preexisting, correctable mechanical issues that significantly depressurize the building envelope (e.g., ≤10 Pa).

5.2.1 Considerations for Mitigation Diagnostic Sample Size in Family Housing

At typical naval installations, it is not unusual to find a large population of virtually identical family housing buildings. However, looks can be deceiving. In most cases, these homes were built in phases over many years; and it is not unusual, especially in construction projects that spanned many years and had different contractors, for changes and modifications to be made to the substructure and building envelope. But within a particular construction phase (built at the same time, using the same building plans, with the same contractor), mitigation diagnostic and mitigation studies have found that most of these housing units have very similar subslab and envelope characteristics. Therefore, it may not be necessary to perform radon mitigation diagnostics within all units of similar type constructed in the same phase. For example, if 30 “Type A” housing units have elevated radon levels and all were constructed during the same phase, then a good starting point would be to perform diagnostics on 3 to 6 randomly selected units (10 to 20%) to determine if they have similar subslab and/or structural characteristics. If this is found to be the case, then mitigation diagnostics may not be needed in the remaining Type A units. Conversely, if six “Type B” housing units have elevated radon levels, the best approach would be to perform mitigation diagnostics in all of them. With respect to units of similar type that were built in different phases, it is recommended that these units be treated as different types of units and diagnostics be performed accordingly. If in doubt, simply perform diagnostics on all units.

5.2.2 Collateral Mitigation SSD Diagnostics in Family Housing

As was discussed in Section 5.1.8, if aggregate is present under a structural member, then there is a chance that the LFE extends past that structural member into other subslab areas (Figure 60). In multifamily housing, this means there is a possibility that one SSD system could control radon levels in two or more housing units within the same building. The prevalence of this situation in multifamily housing is not exceptionally high, only about one in four units. However, in cases where SSD diagnostics are being performed in multifamily housing, it is recommended that a 3/8 in. hole be drilled in adjacent housing units to either prove or disprove the possibility of collateral communication. The cost savings is not only the SSD installation cost but also the cumulative maintenance and energy costs for the remaining lifetime of the that building for an unneeded SSD mitigation system.

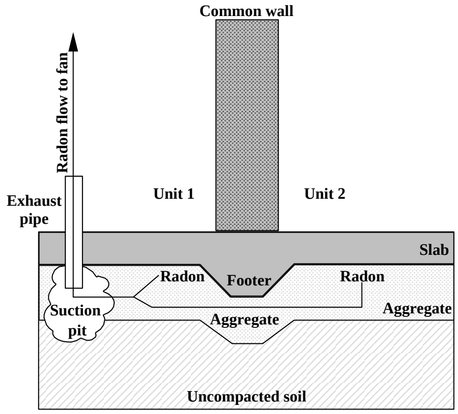


Fig. A. Collateral communication under the footer

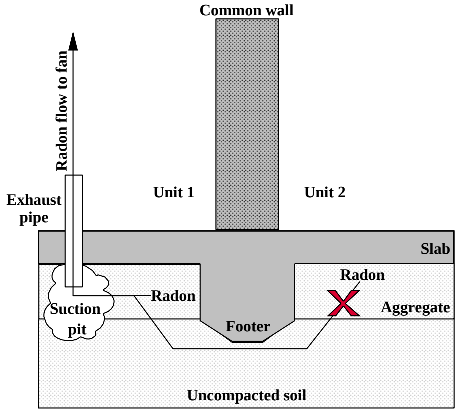


Fig. B. No communication under the footer

Figure 60. Collateral mitigation.

5.3 NONRESIDENTIAL MITIGATION DIAGNOSTIC APPROACHES

Because most of the time radon levels in nonresidential buildings vary significantly from room to room (Section 3.2.2), the diagnostics approaches are different from those used in family housing. The primary reason that radon levels vary so much from room to room in nonresidential buildings is the influence of building mechanical systems on both radon entry and retention (Figure 61). Nonresidential buildings with significant mechanical issues (e.g., < (–) 10 Pa shell pressure) can be mitigated, but the number of SSD systems required to compensate for the negative building envelope pressure increases dramatically as well. The reason is that SSD mitigation works based on the fact that air flows (radon is a gas, like air) from high to low pressure. If the building shell pressure is more negative than the vacuum under a particular area of the slab, then radon will still flow into the building. In the real-world example provided in Figure 62, mechanical diagnostics determined that the HVAC unit could not be restored to installation design specifications because of performance degradation and supply duct leakage (replacement of the entire mechanical system was not an option; nor was the installation of a stand-alone DOAS). SSD diagnostics performed in the building at (–) 35 Pa (as found), (–) 10 Pa (bathroom fans off) and 0 Pa found that the LFE was highly dependent upon the building envelope pressure. If the building could have been brought to 0 Pa, only one SSD system would have been required; two SSD systems would have been required at (–) 10 Pa. However, because of the current negative envelope pressure, (–) 35 Pa, could not be corrected, six SSD systems were required to mitigate.

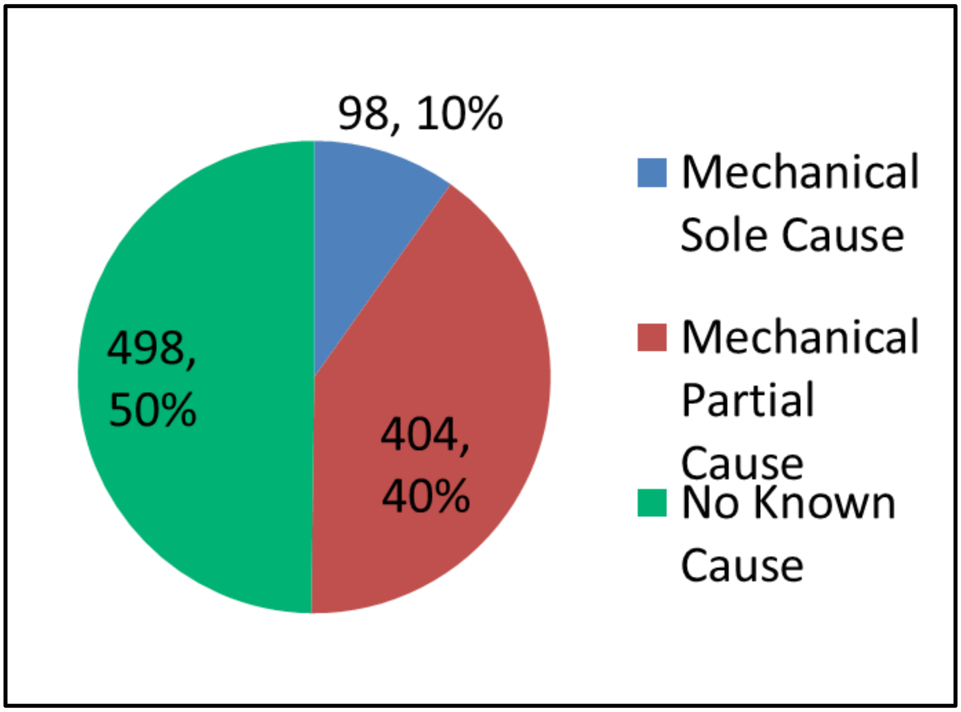


Figure 61. Primary reason for elevated radon levels in 1000 nonresidential rooms.

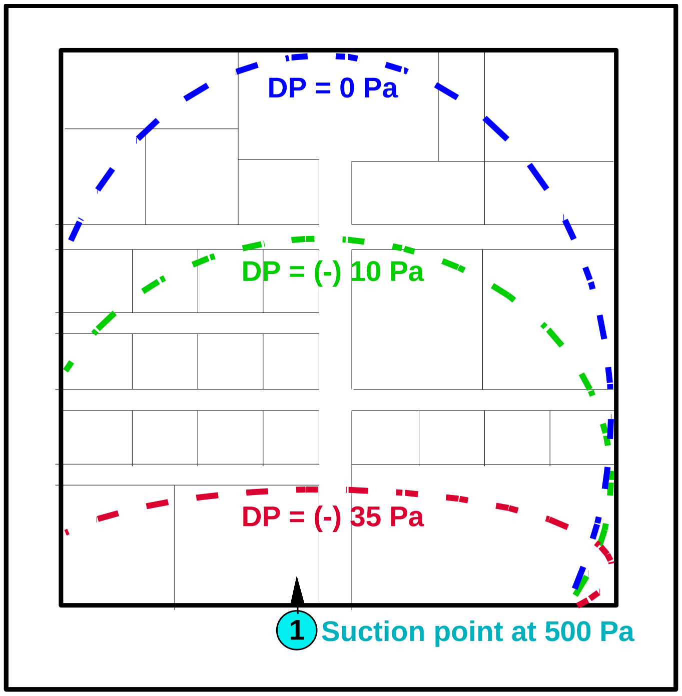


Figure 62. Example of LFE vs. envelope shell pressure.

Because of the impact and prevalence of HVAC issues in nonresidential buildings, typically more than one diagnostic technique will be required to determine the best mitigation choice(s). Therefore, the time line for nonresidential mitigation diagnostics will be considerably longer than that for family housing and may involve the use of different contractors (e.g., a radon mitigation contractor and a mechanical contractor). In the mitigation diagnostic planning stages, the first step is to determine the distribution pattern of the elevated radon (Figure 37). If there is a uniform pattern of either type (Figure 37), then in most cases there is an underlying mechanical issue that needs to be addressed; thus, mechanical inspection should be performed first. In addition, during the mitigation diagnostic planning stages, it is recommended that a building envelope DP measurement (Section 5.1.6) be performed as well. If the building envelope is < (−) 10 Pa, then a mechanical inspection should be performed as well. The decision on how to proceed depends upon these mechanical findings. For example, if mechanical inspections determine that HVAC adjustments and/or repairs are feasible, then those should be implemented and the building retested. If elevated radon levels are still present, then SSD diagnostics should be performed. If SSD mitigation is not viable, then shell leakage (Section 5.1.5) and air exchange measurements (Section 5.1.4) should be performed. The combination of these two diagnostics will provide insight as to which mitigation method (SP or ERV) would be the most practical. If neither is practical, then DOAS would be the only remaining mitigation choice.

If envelope shell pressure measurements (Section 5.1.5) indicate that there are no underlying mechanical issues in the building, then SSD mitigation diagnostics should be performed next. Estimating the number of diagnostic test holes needed depends upon the number of rooms with elevated radon levels; their proximity to one another; the presence or absence of grade beams, interior footings, and foundations; and the type, depth, and level of compaction of the subslab subbase. Most of this information can be located in the building construction plans. With respect to subslab structural members (i.e., grade beams, interior footings, and foundations) a lot depends upon the presence or absence of aggregate between the structural member and the soil. For example, if the building plan cross-sections of these subslab members indicate that they are residing on compacted earth, in all likelihood, the LFE will terminate at that structural member. However, if aggregate is present (even as little as 1–2 in.), there is a chance that the LFE will extend beyond the structural member into the adjoining subslab area(s). Although most foundation plans contain a cross-section of the subslab showing the bottom of the slab, the vapor barrier, and the depth and composition of the layer of subbase atop of the soil, in practice, directly correlating this information to estimate the LFE and SPT can prove difficult. Whereas 6–8 in. of prewashed 1/2 to 3/4 in aggregate has been known to exhibit exceptional LFE (5000 ft^2 is not uncommon), the LFE in compacted clay or sand can be as little as 100 ft^2 in extreme cases. Unfortunately, the only way to know for sure is to drill the 1.5 in. to 3 in. diagnostic hole and examine the subbase directly.

Another key difference between family housing and nonresidential mitigation is the extent of radon mitigation. Historically, at the conclusion of the mitigation diagnostics, a decision was made to either mitigate just the few rooms with the elevated radon levels or to take additional mitigation measures to potentially prevent elevated radon levels from occurring in other rooms or areas of the building. The assumption made was that a building with a predisposition for elevated radon levels was more likely to develop problems in other rooms in the building over time. However, ongoing studies currently being conducted by the Navy have found that unrenovated, previously mitigated buildings that are being operated at or near the mitigation envelope pressure are no more likely over time to develop elevated radon levels in additional rooms than other buildings with no previous history of elevated radon levels. In addition, if elevated radon levels are found in later surveys (NAVRAMP requires a retest every 5 years at installations with known elevated radon potential) of these previously mitigated buildings, in almost every case, the building envelope pressure is found to be significantly more negative (Figure 63). Therefore, based upon these studies, it is more prudent to take additional mitigation measures based on the likelihood that the building envelope pressure would become more negative over time.

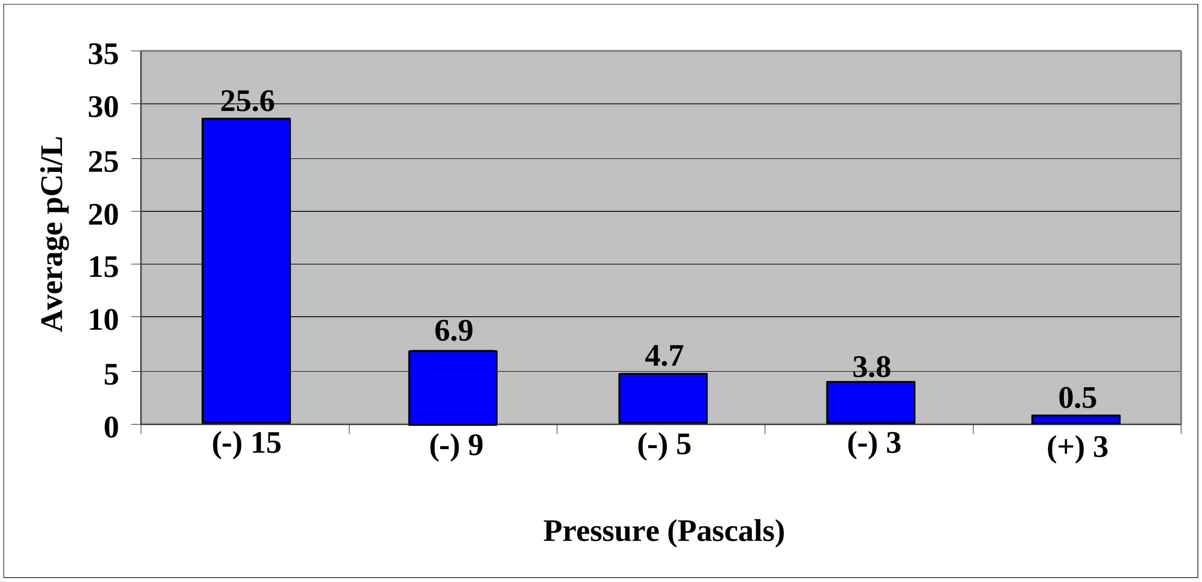
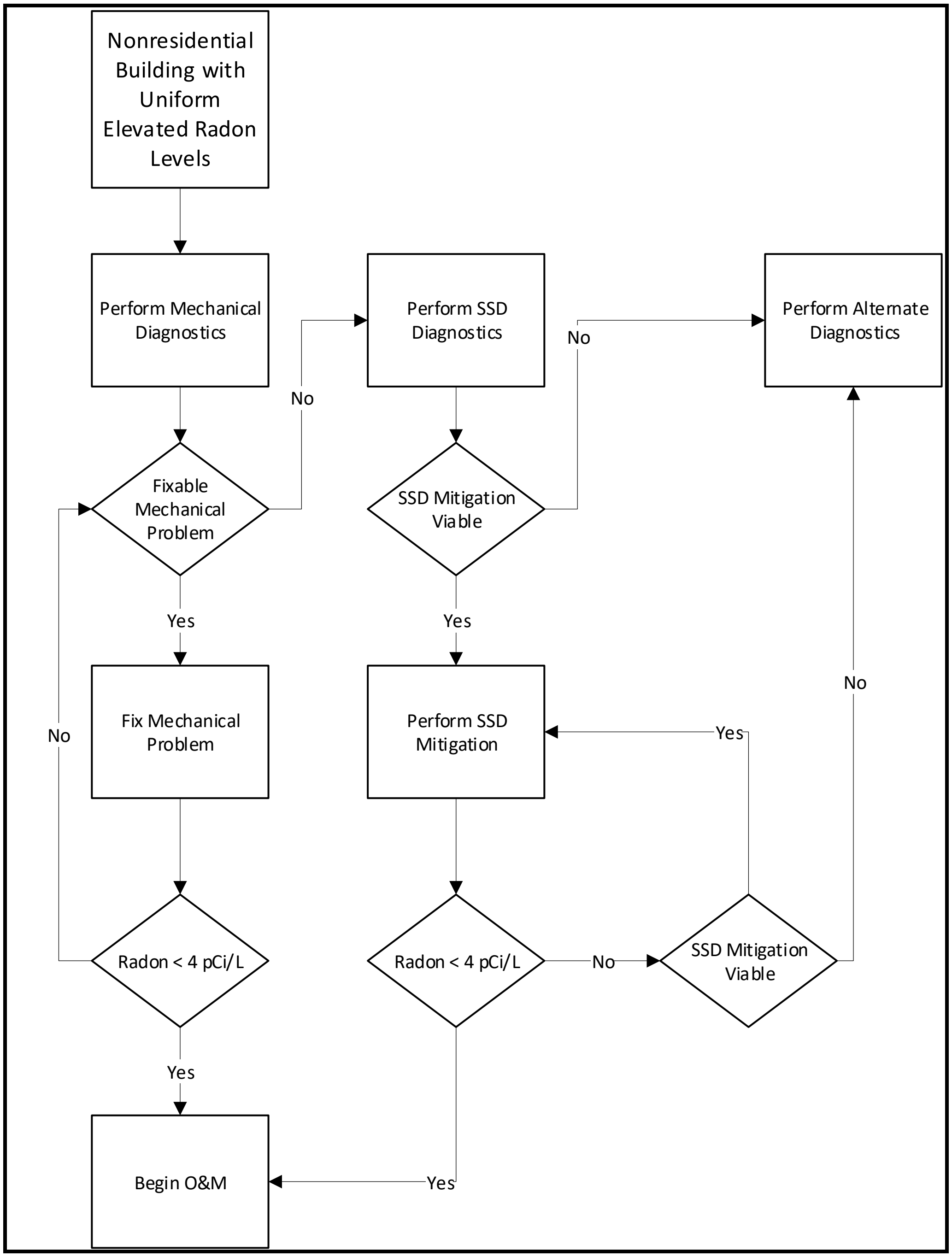
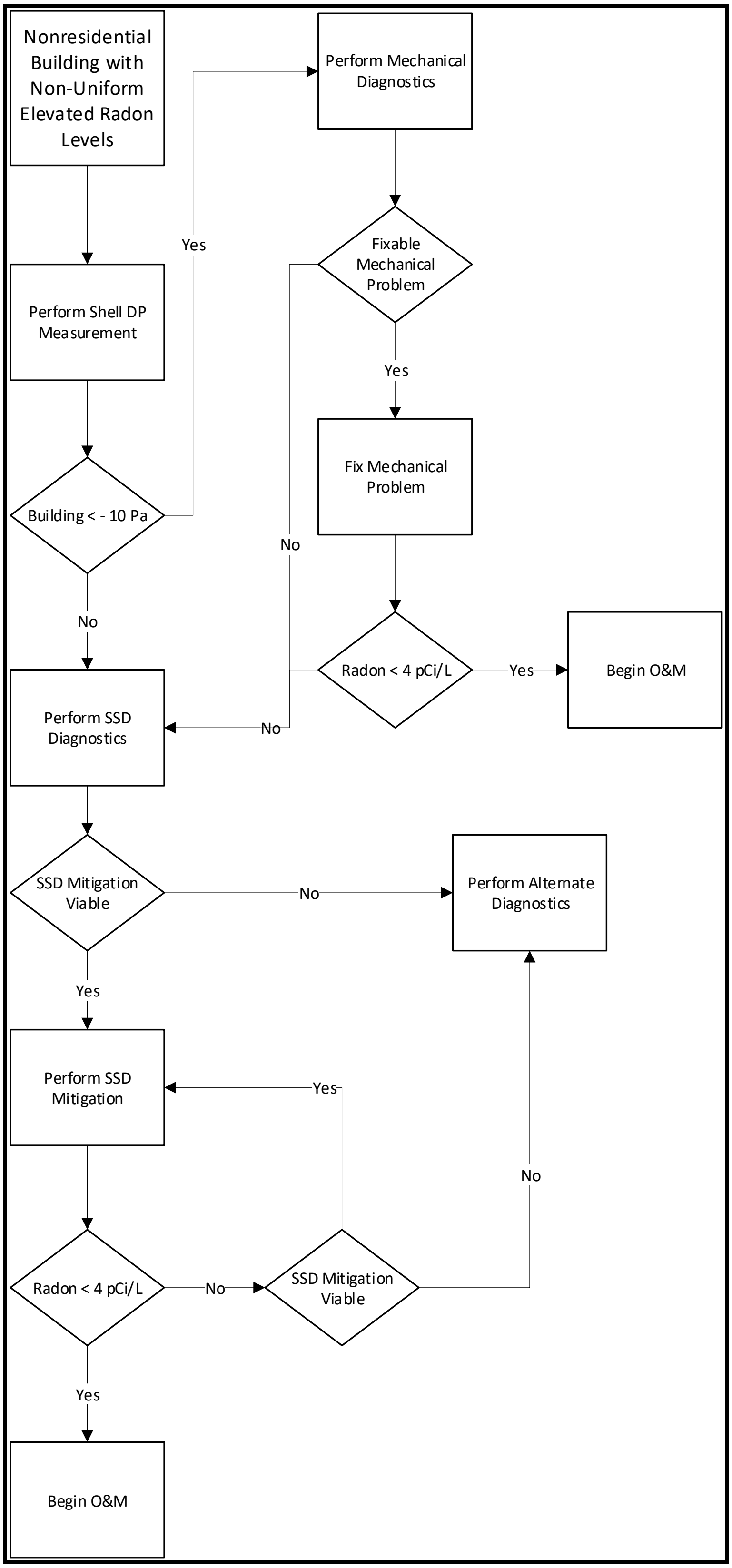


Figure 63. Example of negative building envelope pressure vs. radon levels.

In summary, the most difficult aspect of nonresidential mitigation diagnostics is knowing where to start. As mentioned earlier, a review of the building plans and the radon distribution pattern (Figure 37) is typically a good indicator for selecting the first few diagnostic steps. Flowchart 2 is a suggested starting point for diagnostics within buildings with elevated radon levels in sections or the entire building. Flowchart 3 is a suggested starting point for diagnostics within buildings in which a mechanical problem is not initially suspected.



Flowchart 2. Uniform radon distribution pattern starting point.



Flowchart 3. Nonuniform radon distribution pattern starting point.

6. OPERATION AND MAINTENANCE OF MITIGATION SYSTEMS

It is a well-established fact that all passive and active radon mitigation systems will eventually fail (e.g., sealant will crack, SSD fans burn out, filters become clogged, drive belts break etc..). To ensure continued mitigation, EPA (EPA 402-R-93-078 [EPA 1994b]) and NAVRAMP recommends that required maintenance, periodic inspections and retesting be performed. However, studies have shown that the specific maintenance requirements and frequency of periodic inspections vary by mitigation type. For example, an SSD mitigation system requires only periodic inspections to ensure that the fan is still operating while SP mitigation systems sometimes require monthly filter cleaning and periodic building shell pressure checks. With respect to active mitigation durability, SSD mitigation has proven to be the most durable (some Navy SSD systems are > 30 years old) followed by SAM, and ERV. The least durable of all mitigation methods is mechanical adjustments/modifications (Section 4.3.7) where < 50% of the buildings are still mitigated after 5-years.

This section provides generic information for the Operation and Maintenance (O&M) of the most common mitigation systems currently installed at naval installations worldwide. In case of conflict, the installation should always defer to the mitigation installers maintenance recommendations.

6.1 O&M OF PASSIVE MITIGATION AND RRNC SYSTEMS

Passive sealing is very much application-specific and thus does not easily fit a standard O&M checklist. Therefore, a customized O&M checklist must be developed. The most common form of passive mitigation is the sealing of cracks and other radon entry pathways with polyurethane caulk. In other cases, expansion foam, concrete patch may have been applied. Therefore, the inspection would need to verify that the caulk/expansion foam/concrete is still adhering to the surfaces and has not been cracked or been damaged. If deterioration is found then resealing would be required.

Within naval communication and server facilities there is almost always an underground cable vault. The gaps around the cables or wires in the cable vault allow for the unrestricted entry of radon into the building. These entry pathways cannot be permanently sealed (this includes the use of expansion foam) due to periodic inspection requirements of the wire or cable and the future potential use of the unused pathways. However, they can be sealed with duct seal or putty and the unused ones with tampered conduit cap plugs which can be removed and reapplied as required. O&M inspection would ensure that all the openings were still sealed and that the duct seal or putty was still pliable (with age this material will shrink and crack) and the tapered caps were still in place. If deterioration if found then resealing would be required.

Under NAVRAMP, inspection of the passive seals is required every 2-3 years and there are no O&M test requirements, but monitoring testing of the building is required every 5-years.

For buildings equipped with RRNC systems, there are no inspection requirements, however monitoring testing of the building is required every 5-years. If the RRNC system is activated, the O&M requirements for SSD mitigation systems would apply.

6.2 O&M OF SUBSLAB DEPRESSURIZATION (SSD) MITIGATION SYSTEMS

SSD mitigation uses a pipe inserted through the slab and connected to a fan (Figure 64, Pictures 30 to 32). When the fan is activated, the area beneath the slab (subslab) is depressurized. The resulting depressurization prevents radon entry into the living area by redirecting the subslab radon into the pipe for discharge into the atmosphere, where it is harmlessly diluted. Generally speaking, an SSD system consists of two major components: the exhaust pipe and the mitigation fan. Of these two components, only the fan will normally need to be replaced during the remaining lifetime of the building. To determine if the fan is working properly, it is recommended that the occupant perform a monthly visual inspection of the U-tube on the fan. If the oil level reads between 0.3 and 4.0 on the scale, then the fan is operating properly (Figure 65). If the oil level is reading 0, then the occupant should contact the phone number on the decal. A decal placed next to the U-tube provides detailed instructions and contact phone numbers. The only required maintenance of the U-tube is the infrequent addition of oil. If oil is needed, common cooking oil (e.g., Mazola® oil or the equivalent) may be used or the U-tube can be replaced. Petroleum-based oils or fluids should not be used because of the potential for poisoning small children. Before oil is added to the U-tube, the fan should be turned off either at the exterior switch or by tripping the circuit breaker. Using an eyedropper or plastic drinking straw, oil can then be added a drop at a time until the level equals 0, or the U-tube can simply be replaced. Pictures 18 and 19 show typical U-tube installations. Another type of performance indicator is the magnehelic pressure gauge (Picture 20). The illuminated light box (Picture 21) relies on an electrical pressure sensor to trigger one of two LED lights (red indicating fan is off, and green indicating fan is on). Maintenance for an illuminated light box is limited to infrequent replacement of the 10-year LED bulbs and pressure sensor.

Depending upon the orientation of the building and the type of system installed, the U-tube can be mounted on the exterior of the building inside a manometer box (Picture 19) or mounted on the pipe near the floor penetration (Picture 18). Magnehelic pressure gauge (Picture 20) can also be mounted on the pipe or in an enclosure on the outside of the building. An illuminated light box (Picture 21), on the other hand, can be located near the system or at a convenient location some distance from the system for remote viewing. In the private sector, routine maintenance of the mitigation system is the responsibility of the individual homeowner or building owner, and maintenance is usually performed by qualified personnel after system failure. Evaluation of the SSD systems installed at other military facilities identified several critical parts and components that should be checked on a regular interval. This maintenance is recommended to prevent water leakage into the building and loss of exterior components during high winds. With these considerations in mind, it is recommended that each component and part listed in Table 12 be inspected in accordance with the proposed schedule. To assist with the identification of the components, a "typical" SSD system has been broken into three assemblies (pipe, fan, and roof flashing) and is illustrated in Figs. 8, 9 and 10).

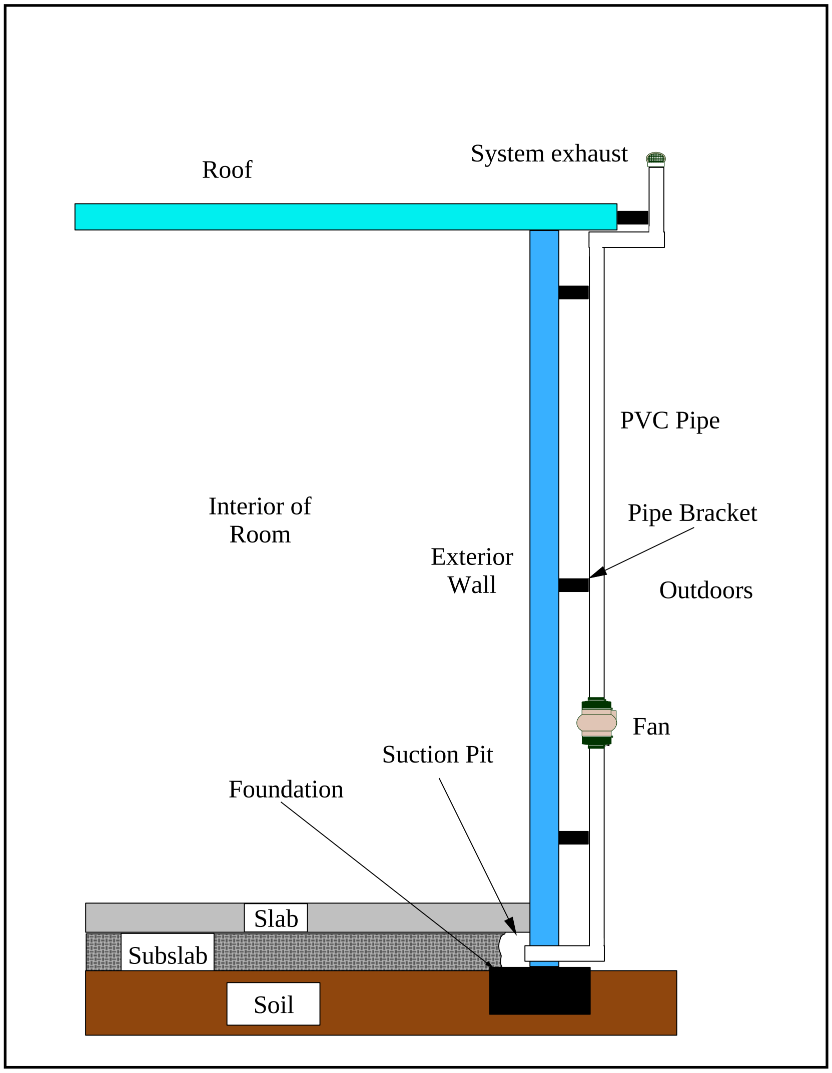
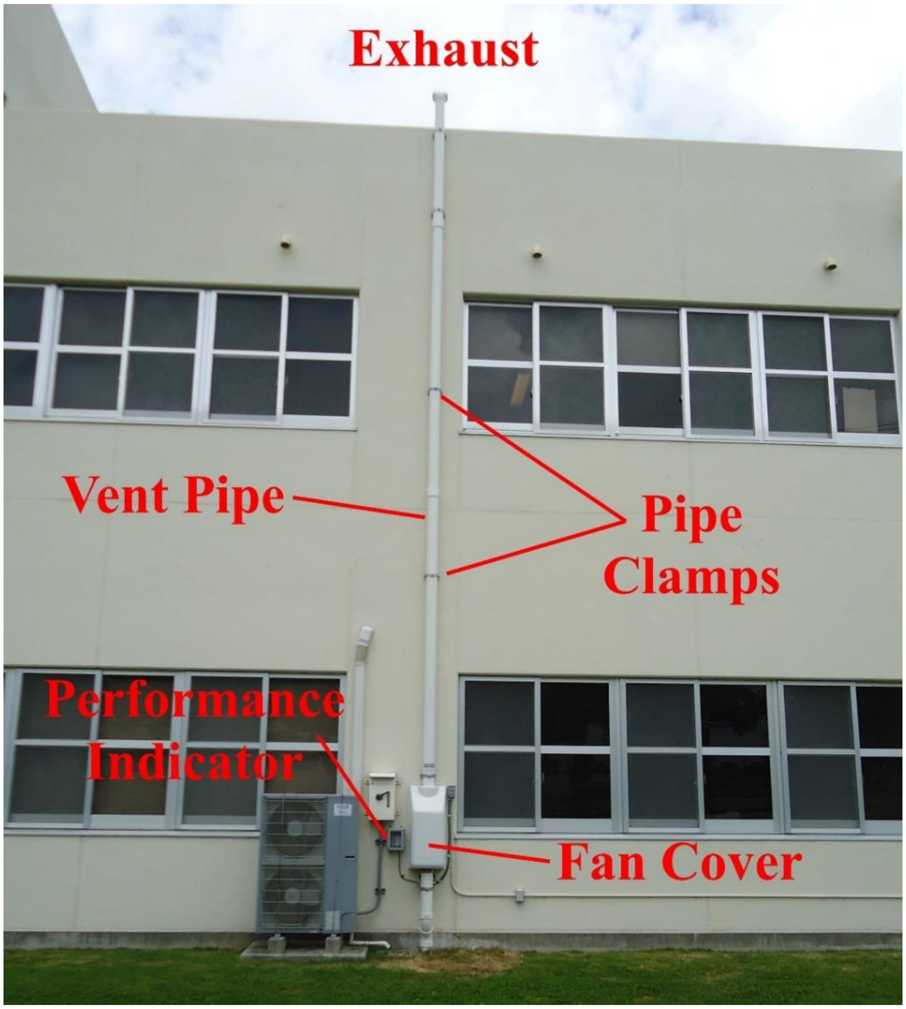
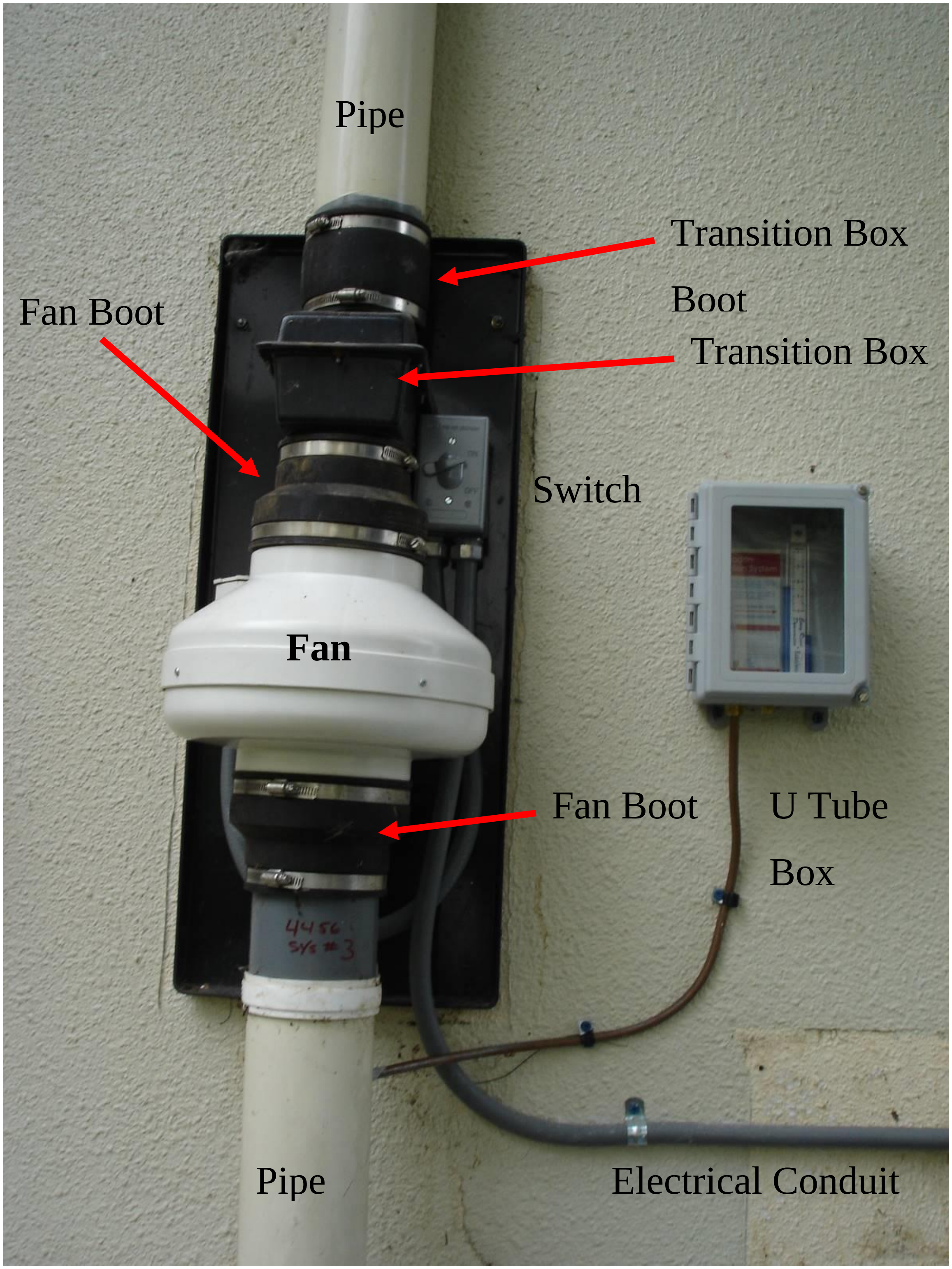


Figure 64. Basic components of an SSD mitigation system.

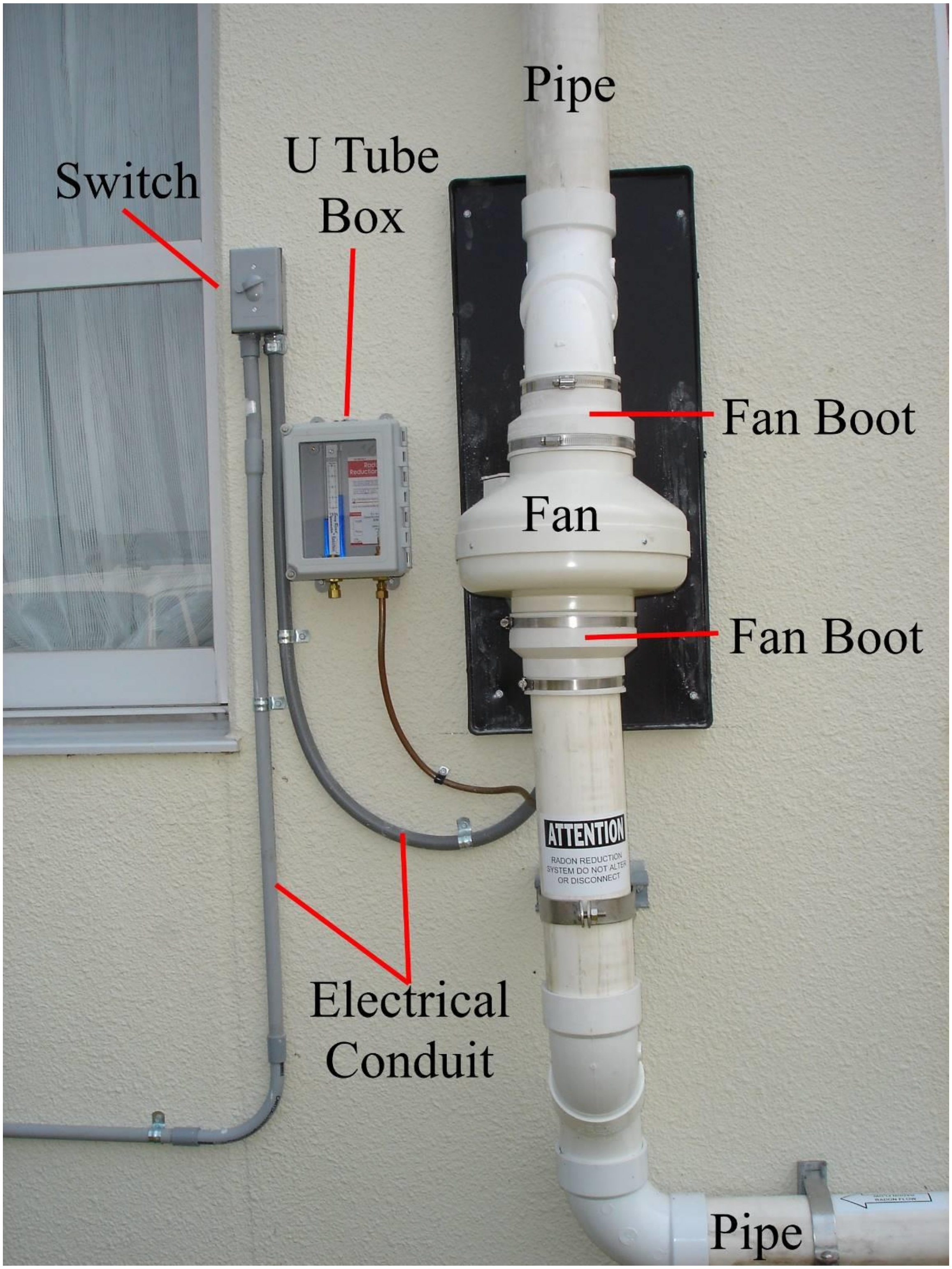
Problems in an SSD mitigation system generally are caused by failure of the mitigation fan or the loss of vacuum under the slab. Table 13 summarizes the most common problems and proposed corrective actions for SSD mitigation systems. Table 14 provides a trouble shooting list for the most common problems with SP systems.



Picture 30. Typical SSD mitigation system.



Picture 31. SSD mitigation system with transition box.



Picture 32. SSD mitigation system without transition box.

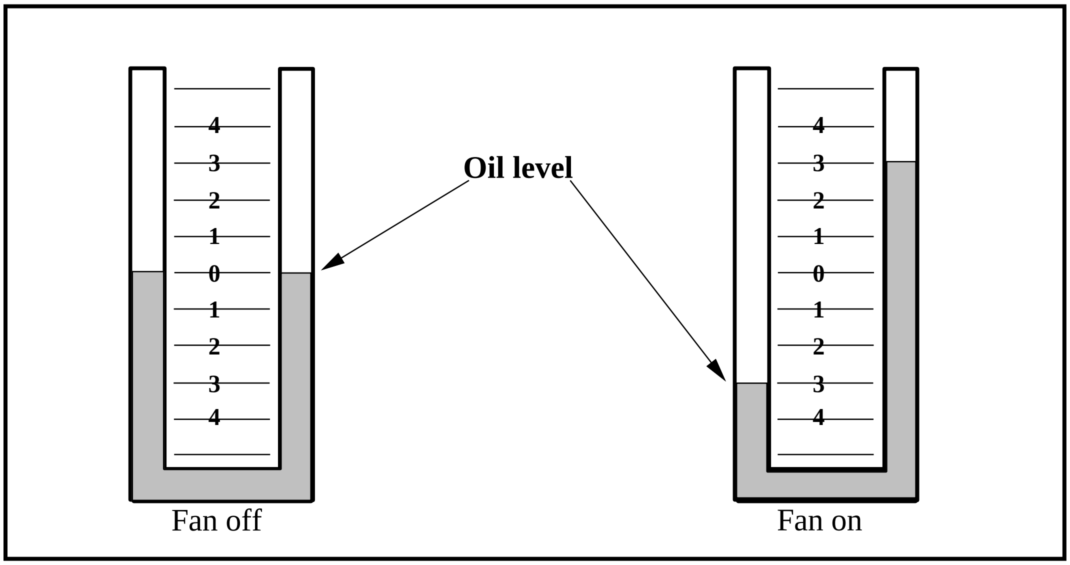


Figure 65. Typical U-tube.

Table 12. SSD components requiring routine inspection.

Component	Check for	Corrective action	Recommended frequency of inspection
U-tube (Figure 65)			
U-tube	Fan operation	Check electrical connection and switch or replace fan	Monthly by occupant or quarterly by installation or other designated party
U-tube	Oil level	Add oil	2-3 years
Pipe assembly (Figure 66)			
Pipe/slab seal	Leakage	Apply additional polyurethane caulk	2-3 years
Interior wall/pipe seal	Leakage	Apply additional polyurethane caulk	2-3 years
Exterior wall/pipe seal	Leakage	Apply additional polyurethane caulk	2-3 years
Clamp nut	Tightness	Tighten nut	2-3 years

Table 12. SSD components requiring routine inspection (continued).

Pipe-mounted fan assembly (Figure 67)			
Rubber boot	Cracking or sagging, fan seated level	Replace boot	2-3 years
Fan operation	Excessive noise, vibration, or not operating	Replace fan	2-3 years
Rubber boot/pipe seal	Leakage	Replace boot	2-3 years
Flex conduit electrical condition	Cracking of conduit and deterioration of liquid-tight connectors	Replace conduit and liquid-tight connectors	2-3 years
Switch and switch and switch cover gasket	Functional switch and seal of box gasket	Replace switch and gasket	2-3 years
Conduit C clamp	Tightness and corrosion	Tighten or replace C clamp	2-3 years
Hose clamp	Tightness	Tighten	2-3 years
Roof flashing (Figure 68)			
Flashing	Water leaks and cracking	Replace or reseal flashing	2-3 years

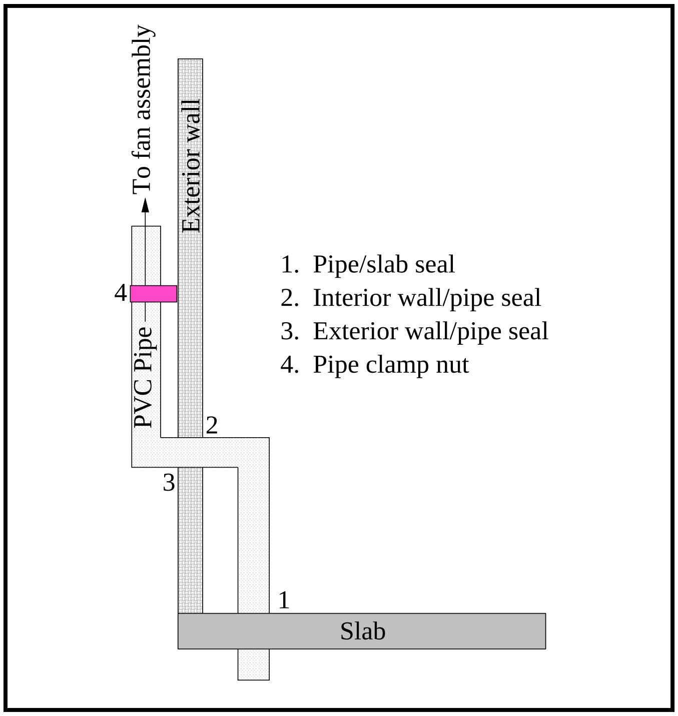
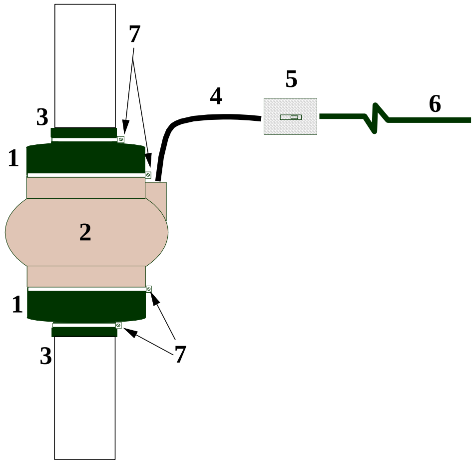


Figure 66. Components to inspect in an SSD system pipe assembly.



1. Rubber boot condition and fan seal
2. Fan operation
3. Rubber boot and pipe seal
4. Flex conduit electrical condition
5. Switch and switch cover gasket
6. "C" clamp tightness
7. Hose clamp tightness

Figure 67. Components to inspect in an SSD system pipe-mounted fan assembly.

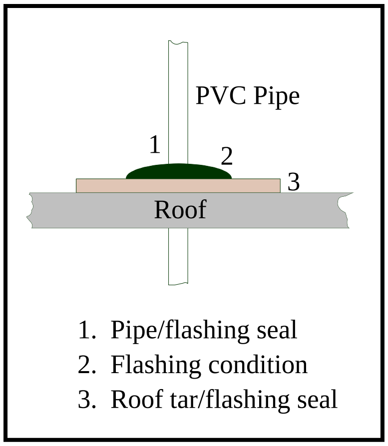


Figure 68. Components to inspect in an SSD system roof flashing assembly.

Table 13. Troubleshooting SSD mitigation systems.

Problem	Possible solution
Fan is not operating	1. Verify that the switch is on and the circuit breaker has not tripped 2. Check electrical connections from the switch box to the fan 3. Replace mitigation fan
Pipe has a noticeable vibration sound	1. Make sure that the fan is level 2. Verify that the base of the fan is not in contact with the pipe. If boot is sagging, replace boot 3. Replace fan
Fan is vibrating	1. Make sure that the fan is level 2. Replace fan
Fan is operating, but U-tube reads <1.5	1. Verify that additional oil is not needed in the U-tube 2. Inspect the U-tube and verify that it is connected to the pipe and that the tubing has not been crimped 3. Verify that no obstructions are present in the system exhaust 4. Inspect the boot/fan seals for air leaks 5. Check floor/pipe seals for air leakage 6. Inspect PVC pipe for holes 7. Replace mitigation fan

Table 13. Troubleshooting SSD mitigation systems (continued).

Problem	Possible solution
Fan appears to be operating within normal parameters, but building/room is no longer <4 pCi/L	1. Verify that U-tube has sufficient oil 2. Verify that no obstructions are present in the system exhaust 3. Inspect the boot/fan seals for air leaks 4. Check floor/pipe seals for air leakage 5. Inspect PVC pipe for holes 6. Repeat radon test 7. Replace fan 8. Review repair and renovation history of building since the system was last verified to be functioning properly. Have renovations occurred that may have reduced the air change rate? Has a new air exhaust system been added? If the answer is yes to either question, a supplemental suction point may be required 9. Perform lateral field extension measurements to determine if vacuum gradient has changed. Install new suction point in area without vacuum
System has audible whistling sound while operating	1. Inspect pipe for holes 2. Inspect PVC joints for leakage 3. Inspect pipe/slab seal for leakage
During heavy rains, water leaks around pipe	1. Inspect wall/pipe seal for leakage 2. Inspect pipe/floor seal for leakage 3. Inspect flashing assembly for cracks or holes

Appendix C contains an example of a data form used for SSD O&M inspections.

6.3 O&M CONSIDERATIONS FOR MITIGATION MECHANICAL SYSTEMS

ERV, Type 2 SP systems, and DOAS mitigation systems all require routine maintenance (e.g., changing of filters, cleaning of screens, evaporative or condensing coils, lubrication etc..). These types of tasks are considered routine maintenance items for every naval installation maintenance shop. However, they may require some lead time to obtain filters and other consumable maintenance items and become familiar with the proposed mechanical unit. In addition, they may also be able to provide based on experience suggestions as to which manufacturer or model to purchase. Incorporation of mitigation mechanical systems into the routine maintenance cycle at an installation is much easier if it is identical or very similar to existing equipment. In addition, other questions such existing as electrical service to a particular building can also be addressed and answered. Once the mitigation mechanical system has been installed, a detailed routine and preventative maintenance schedule should be provided to the installation mechanical maintenance shop along with copies of the operations manual.

6.4 O&M OF SHELL PRESSURIZATION SYSTEMS

An SP system retards radon entry by mechanically introducing sufficient outdoor air to induce a positive pressure across the slab (typically 4 to 6 Pa) and into the soil. Applying pressure across the building shell reverses the natural flow of radon from the soil into the living area. Therefore, the air flows from the living area into the subslab, preventing radon entry. The downside of an SP system is that all windows and doors must be kept closed to maintain mitigation. Small openings, such as an entry door left ajar or a window left cracked open, will result in the radon levels reverting to their unmitigated levels. Also, as door and window seals deteriorate over time, additional fresh air must be drawn in to maintain mitigation.

The following routine maintenance is recommended for an air intake SP system or as required by the mitigation installer or manufacturer:

1. Clean or replace the air intake grill air filter and the inside air filter quarterly or as recommended by the mitigation installer.
2. Perform shell pressure, indoor temperature and humidity checks twice per year.
    a. If required, adjust shell pressure to 4 to 6 Pa or per mitigation installers requirements.
3. For Type 2 SP systems, cleaning of the evaporator and condensing coils will also be required. This cleaning and other maintenance items should be as required by the manufacturer.

For properly maintained and inspected SP mitigation systems, there are no O&M test requirements, however monitoring testing of the building is required every 5-years.

Table 14 lists troubleshooting techniques for air intake SP mitigation systems if, in the future, mitigation failure occurs or the building can no longer be pressurized to 4 to 6 Pa.

Table 14. Troubleshooting SP mitigation systems.

Problem	Possible solutions
Building is <4 Pa shell pressure (indoor to outside)	1. Verify that the mechanical blower is running continuously and properly 2. Inspect intake grill for blockage 3. Clean intake grill air filter 4. Adjust air intake damper to increase outdoor airflow 5. Inspect the mechanical collar for leakage. Repair leak as needed 6. Inspect shell for any significant leaks around windows and exterior doors. As appropriate, replace door seals or caulk any cracks around windows and doors
Building is >6 Pa pressure (indoor to outside)	1. Adjust air intake damper to decrease outdoor airflow 2. Clean central mechanical return air filter 3. Inspect mechanical collar for leakage. Repair leak as needed
Building is >4 pCi/L	1. Verify that the blower is running continuously and properly 2. Check shell pressure with digital micromanometer 3. Verify that occupants are not leaving windows and doors open for extended periods of time
Building is >4 pCi/L and shell pressure is between 4 and 6 Pa	1. Repeat differential pressure diagnostic for all major air exhaust systems. Discuss with occupants the frequency of usage of the exhaust systems. Increase airflow accordingly to compensate for largest and/or most frequently used air exhaust system

6.5 O&M OF ENERGY RECOVERY VENTILATION MITIGATION SYSTEMS

ERV systems are commercially available package systems that reduce radon levels by increasing the natural ventilation rate in a building or room(s). Because of differences in design, installation, and materials, no two manufacturers' O&M requirements are exactly the same. Therefore, it is important to review the owner's manual and draft a system-specific O&M plan for each model of ERV at the installation. Common O&M elements to address are:

1. The frequency of changing the air filters and drive belts
2. Lubrication of the drive and blow motors
3. Maintenance of the desiccant wheel
4. The recommended frequency for checking the supply and exhaust flows of the system

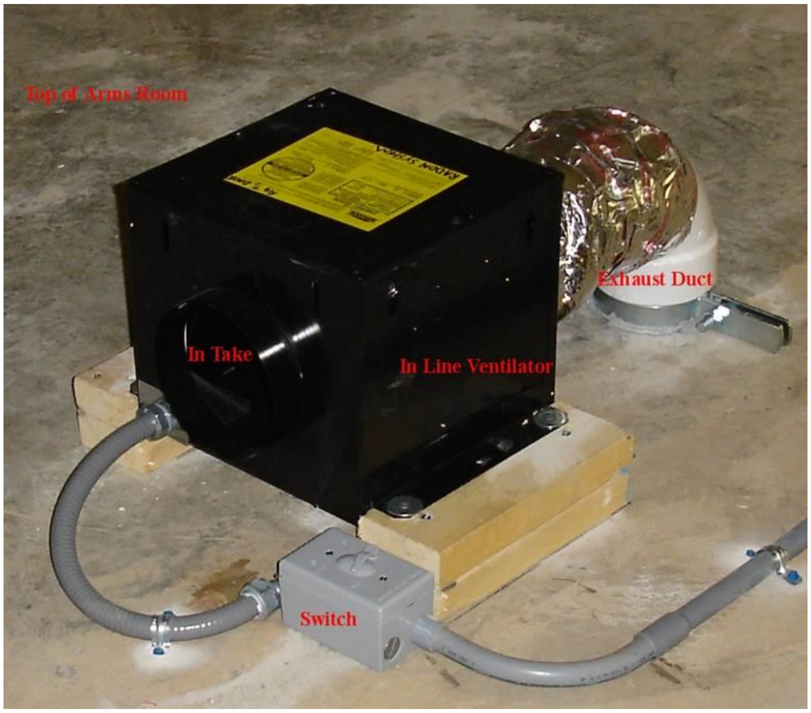
It is important to note that for ERV systems, O&M is not just a good idea—it is mandatory. For example, if the system filters are not changed, the building or room may become depressurized (i.e., the ERV exhausts more air than it is bringing in), resulting in a potential increase in the room's radon levels. In addition, on some ERV models, lack of maintenance of the desiccant wheel could result in a sudden uncontrollable increase in the humidity of the supply air. This condition could result in a catastrophic condensation release followed by the onset of mold. As for O&M inspections, twice per year the temperature and humidity of the room or building should be checked. In addition, the intake and exhaust flows should be checked and rebalanced as needed.

In addition to the routine maintenance schedule, a detailed inspection of the ERV must be performed every 2-3 years. The inspection should include a check of the intake and exhaust flows, building shell pressure, condition of the desiccant wheel, and check of the building's temperature and humidity. For properly maintained and inspected ERV mitigation systems, there are no O&M test requirements, however monitoring testing of the building is required every 5-years.

6.6 O&M OF SUPPLEMENTAL AIR MITIGATION (SAM) SYSTEMS

In general, SAM systems are easy to operate and maintain. The system consists of two basic parts, the electric fan and the duct, neither of which requires any scheduled maintenance. Although, as recommended by the mitigation installer, the intake (Pictures 33 and 34) must be inspected and cleaned. To ensure that it is operating, a fan performance check should be performed twice per year. This can be accomplished by confirming the blower is exhausting into the room (e.g., smoke test, strip of paper) or by checking the system performance indicator (Picture 35).

Every 2-3 years, it is recommended that the exhaust rate of the blower be checked using a pitot tube, face velocity probe, or other suitable measuring device to confirm that the blower is still providing the required flow. If the air volume is found to be more than 10% less than the installation air flow the fan should be replaced or a O&M radon test performed to determine if the room is still mitigated. In cases where the fan is replaced with a blower which provides 90% or less of the original blower, the room(s) should be retested. For properly maintained and inspected SAM mitigation systems, there are no O&M test requirements, however monitoring testing of the building is required every 5-years.



Picture 33. SAM components with box fan.

Picture 34. SAM components with centrifugal fan.

Picture 35. SAM performance indicator.

6.7 O&M OF A DEDICATED OUTDOOR AIR SYSTEM

DOAS systems are commercially available package systems that reduce radon levels by dilution or pressurization. Because of differences in design, installation, and materials, no two manufacturers' O&M requirements are exactly the same. Therefore, it is important to review the owner's manual and draft a system-specific O&M plan for each model of DOAS at the installation. Common O&M elements to address are:

1. The frequency of changing the air filters and drive belts
2. Lubrication of the drive and blow motors
3. Maintenance of the desiccant wheel (if applicable)
4. Evaporator and condensing coils and other component cleaning
5. The recommended frequency of checking the intake/supply air flows

It is important to note that for DOAS systems, O&M is not just a good idea—it is mandatory. For example, if the system filters are not changed, the volume of intake air may drop below the volume required for mitigation. In more severe cases the unit could overheat and burn out. If present, lack of maintenance of the desiccant wheel could result in a sudden uncontrollable increase in the humidity of the supply air. This condition could result in a catastrophic condensation release followed by the onset of mold. With respect to O&M inspections, twice per year the unit should be inspected to verify that no adjustments or tampering has occurred. The supply air volume, building temperature, humidity and shell pressure (if applicable) should also be checked.

In addition to the routine maintenance schedule a detailed inspection of the DOAS must be performed every 2-3 years. The inspection should include a check of the intake flows, building shell pressure, condition of the desiccant wheel (if present), and check of the building's temperature and humidity. For properly maintained and inspected DOAS mitigation systems, there are no O&M test requirements, however monitoring testing of the building is required every 5-years.

6.8 O&M OF MECHANICAL REPAIRS, MAINTENANCE AND PERMANENT EXHAUST REDUCTION

If the repair or correction of a routine maintenance item on a HVAC unit or the permanent reduction of building exhaust mitigated the room or building, under NAVRAMP the need to perform performance checks or routine inspections is not required. The only requirement is performing monitoring testing every 5-years. Although, in the case of routine maintenance items (filter replacements or intake screen cleaning) it may be prudent to perform spot checks to verify that the needed routine maintenance did get incorporated into the maintenance schedule.

6.9 O&M OF MECHANICAL ADJUSTMENTS, AND BALANCE

Unlike other mitigation methods, there are no commercially available performance indicators for mechanical adjustments and balance. This is unfortunate since mitigation using this method is the easiest to defeat. For this reason, twice per year the following checks are recommended:

- Mitigation by fresh-air incorporation
    - Verify fresh-air damper setting or volume
    - Check indoor temperature and humidity in the building
    - Check building shell pressure if pressurization was the mitigation method
- Mitigation by mechanical balance
    - Inspect all supply and return diffusers for tampering or adjustments
        - If tampering or adjustment is suspected, check exhaust or intake volume of the diffuser with a pitot tube, face velocity probe or flow hood.
    - Check temperature and humidity levels in the building
    - Check building shell pressure if pressurization was the mitigation method

Every 2 to 3 years, perform O&M testing in the room or rooms which were mitigated and retest the entire building every 5-years (monitoring test).

6.10 O&M OF ENERGY SET BACK MITIGATION

Energy set back mitigation failure is typically linked to increases in the duration of the energy setback, decreases in the fresh-air volume of the HVAC, and issues with the controller. Therefore, twice per year the settings on the HVAC controller need to be checked to verify that there has not been an increase in the duration of the energy set back. If these changes are permanent, then a series of CRM diagnostics should be performed to determine if radon levels are still < 4 pCi/L during the occupied periods. Because there is not an acceptable passive radon testing method for this mitigation technique, CRM measurements will be required to document the radon levels within the occupied hours within all mitigated rooms. These measurements must be of 7 to 14 days duration. If CRM diagnostics determined that seasonal HVAC settings were significant, then the CRM measurements must be performed in all seasons identified as being a factor in estimating the annual occupied radon level average. In addition, CRM measurements within the mitigated room or rooms will be required every 2-3 years and during the required 5-year monitoring retest.

7. RADON-RESISTANT NEW CONSTRUCTION

7.1 OVERVIEW OF RRNC

Radon resistant new construction (RRNC) is a scientifically based, architectural and engineering design concept to help reduce radon entry into the living area. RRNC incorporates techniques such as sealing radon soil gas entry points, a means of efficiently collecting radon (commonly referred to a plenum) and then passively venting it to the outside (Figure 69). If testing later finds elevated radon levels within the building, an electric radon mitigation fan can be installed on the vent pipe (commonly referred to as RRNC system activation) to further reduce the indoor radon levels.

Studies performed by EPA and the National Association of Home Builders (NAHB) have found lower average radon levels within housing populations equipped with passive stack systems. Conservative estimates indicate that 25-35% of homes equipped with RRNC will remain below the radon level of concern for the remaining lifetime of the home. A good example of RRNC effectiveness in Navy family housing is a neighborhood in Guam in which 25% of the homes had elevated radon levels (highest result 10.2 pCi/L). Ten years after all the homes had been mitigated, the neighborhood was demolished and replaced with new housing which incorporated RRNC features. Radon testing of the housing after construction was completed and monitoring testing performed over the past 10 years has found no homes with elevated radon levels. This success story should not be interpreted as RRNC makes all homes "Radon Proof". In fact, at the same installation, incorporation of similar RRNC measures in other new residential construction projects did not achieve 100% passive mitigation. Diligence in the form of periodic radon testing is required throughout the lifetime of the structure to ensure a safe indoor environment.

In addition to the passive radon reduction potential, properly designed and installed RRNC systems have an extremely high mitigation success rate if system activation is required. Within naval buildings with properly designed and installed RRNC systems, the success rate has been 100% within family housing and nonresidential buildings. Another key advantage of an RRNC system is that the typical design, and installation cost uncertainties involving rough in mitigation within buildings are eliminated. With an RRNC system measures required to mitigate a building are known. Therefore, mitigation planning and cost projection is greatly simplified.

Another lessor known benefit of RRNC incorporation is energy savings. In SSD mitigation a significant amount of conditioned indoor air is lost. By sealing the slab openings during construction this loss of conditioned air is significantly reduced if system activation is required. Another consideration is the fan. Properly designed and installed RRNC systems typical require fan wattage to depressurize a similar sub slab area. This energy savings over 30 years could be in excess of $1000. Another consideration is number of SSD systems. A general rule of thumb is that a rough-in SSD system in an existing building under ideal conditions will depressurize about 4,000 ft^2 of slab area. However, if grade beams and interior foundations are present, the coverage per SSD can be significantly less. Alternatively, if a soil gas collection network is installed (Section 7.3.6) then the coverage for a single suction point can be up to 10,000 ft^2 of slab area. Therefore, the number of potential SSD systems required for mitigation will be significantly less.

Because of these benefits, the US Navy [OPNAV M-5090.1 (25 Jun 2021)] and USMC [MCO 5090.2 (2018)] require the incorporation of RRNC systems in all new construction at installations or sites which have known or suspected elevated radon potential.

In summary, it is important to note that the incorporation of RRNC features into a building's construction does not mean that the building is "Radon Proof". Buildings equipped with RRNC features still must be tested as required along with other buildings which do not have RRNC. However, if RRNC is installed properly, future mitigation projects will be less expensive, more predictable and have an enhanced probability of success.

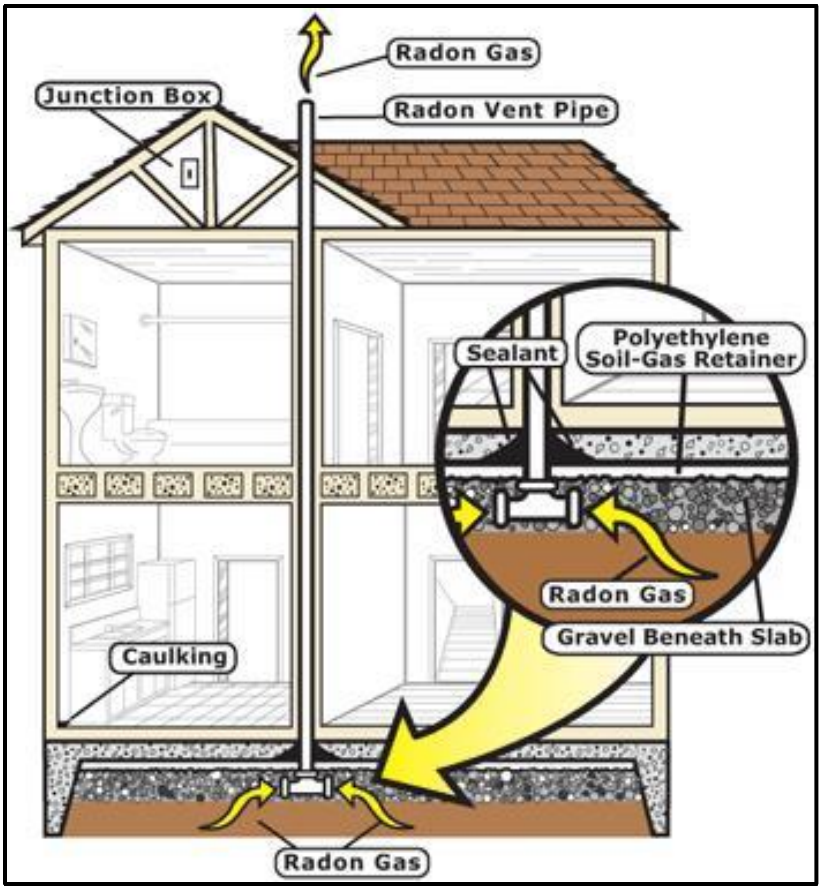


Figure 69. Basic RRNC system components.

7.2 CURRENT RRNC STANDARDS

It is important to note that in 2012, EPA initiated a voluntary consensus-based standards initiative with the radon industry (https://www.epa.gov/radon/radon-standards-practice). The subsequent standards produced by this partnership have superseded and consequently replaced the previous EPA standards and guidance documents. Consequently, for this version of the guidebook a comprehensive review was performed and where applicable, changes were made to the NAVRAMP RRNC guidance. Therefore, for RRNC standards references to be utilized in the development of a design, a statement of work, requests for proposal, performance work statements and similar types of documents use this document, Navy *Radon Assessment And Mitigation Program Guidebook For Naval Shore Installations* (2021) and consult the list in Table 15. These standards can be viewed or purchased on-line at https://standards.aarst.org/ .

In preparing *Navy Radon Assessment and Mitigation Program Guidebook for Naval Shore Installations* (2021) a review was performed to determined how DoD was designing and contracting for radon-resistant new construction (RRNC) designs and installations. A common mistake in most of the designs and requests for proposals (RFP) was referencing radon mitigation standards [UFGS-31-21-13 (2006, 2011, 2018), EPA 402-R-93-078, ASTM E2121-08, 09] which only address the rough in of SSD systems but without the fan, not RRNC. Another common reference was to EPAs *Radon Prevention in the Design and Construction of Schools and other Large Buildings* (EPA/625/R-92/016 June 1994) which also describes along with other radon control approaches the rough-in of a radon vent pipe. This early document makes reference to that only one 6 in. riser is needed to for slabs up to 100,000 ft^2 in area. Like the other standards listed above this is not an RRNC design but a rough-in SSD system without the fan. Subsequent studies by EPA and others have found this single riser totally inadequate with post-activation coverage using commercially available radon mitigation fans under ideal conditions to be about 4,000 ft^2.

Currently there are 3 RRNC radon industry standards (Table 15). As written, these standards will provide the required measures to ensure successful radon mitigation activation (if required). However, it is important to note that these standards were developed for application in private sector single detached homes, a single apartment complex or a school, not for US Navy and USMC application worldwide. An in-depth review of these standards has identified certain areas that required modification or adaption to meet naval installations requirements. The following sections discuss these modifications and adaptations. It is important to note that when designing or contracting RRNC services, the *Navy Radon Assessment and Mitigation Program Guidebook for Naval Shore Installations* (2021) and this technical manual should be used as the primary references and as applicable the RRNC standards listed in Table 15.

Table 15. Current RRNC Standards

Title	**Number**	**Description**
Rough-In of Radon Control Components in New Construction Of 1 & 2 Family Dwellings and Townhouses	ANSI/AARST RRNC-2020	This standard provides minimum requirements for the rough-in of radon control system components in family housing units under construction.
Reducing Radon in New Construction of One & Two Family Dwellings And Townhouses	ANSI/AARST CCAH-2020	This standard provides minimum requirements for the rough-in of radon control system components in new dwelling units under construction.
Soil Gas Control Systems in New Construction of Buildings	ANSI/AARST CC-1000-2018	This standard provides minimum requirements for the construction of any building intended for human occupancy, except for 1 and 2 family dwellings, in order to reduce occupant exposure to radon and other hazardous soil gases. It addresses the construction of buildings to be utilized for multifamily or congregate residential, educational or commercial occupancies.

7.3 IMPLEMENTATION OF RRNC UNDER NAVRAMP

Although the current RRNC standards (Table 15) as written are adequate for private sector application, they were not written for private sector application. For dependent schools and naval family housing the standards as written would suffice. However, naval installations contain a wide variety of unique buildings (e.g., armories, aircraft hangars, large vehicle maintenance shops, SCIFs, etc.) that will have security or structural requirements which in some cases may not be compatible with the RRNC standards. In addition, at some naval installations there are over 300 active SSD systems which require periodic inspection and maintenance. Consideration must be given to the design of these RRNC systems to facilitate future inspection and maintenance. Another consideration is safety. The current standards have the fan (if required) mounted in either an attic or on the roof of a building. To access these areas, fall protection may be required. With respect to roof penetrations, the potential for a leak is always present. Another consideration is time. It is not unusual for a building to not have any radon issues until many years or even decades later. Therefore, the possibility that a building has an RRNC system may be forgotten.

The following sections highlight lessons learned over the past 25 years in RRNC system design and installation within the DoD and provide design recommendations.

7.3.1 RRNC System Radius of Influence

In any RRNC system design, the objective should be to project a minimum of 4 Pa of vacuum under the entire slab with a commercially available radon mitigation fan. The distance from the suction point to the (–) 4 Pa vacuum (Figure 70) is called the radius of influence (ROI). For residential applications, the (–) 4 Pa contour line will always be sufficient. But, in new nonresidential buildings most of the time the building shell pressure is neutral to slightly positive. Over time as the performance of the HVAC degrades, a negative shell pressure will develop. This decrease in shell pressure will cause a corresponding reduction in the ROI. Consequently, if the RRNC system requires activation, the ROI may be insufficient to depressurize the slab area of interest. A review of 500 naval nonresidential buildings with negative shell pressure has identified buildings with up to (-)50 Pa of negative shell pressure. However, an overwhelming majority of them are between (-)1 to (–)8 Pa. Therefore, it is recommended for nonresidential buildings that the RRNC system be designed with a (–)8 Pa ROI.

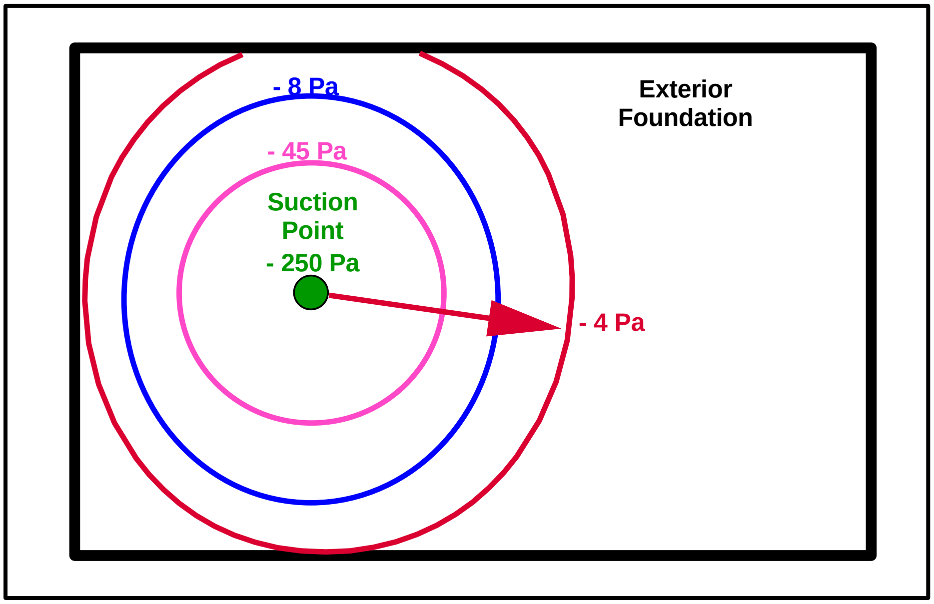


Figure 70. Radius of influence.

7.3.2 Subslab Components

A common misconception is that an RRNC system can be designed based upon the size of the slab alone. However, in some cases, grade beams (a footing component of the buildings foundation), and utility trenches and tunnels and other structural members can greatly reduce or abruptly terminate the radius of influence (ROI) of a radon vent pipe (Figure 71). To ensure complete coverage of the slab, an additional suction point or an opening either through or under the grade beam would be required to ensure vacuum coverage. Another option is to place aggregate (Section 7.3.3) under the grade beam to allow for radon to flow to the vent pipe (Figure 72). In larger, more complex slabs the installation of a soil gas plenum (Section 7.3.6) may be required. Additional options to extend the ROI and slab coverage are addressed in CCAH-2020 and CC-1000.

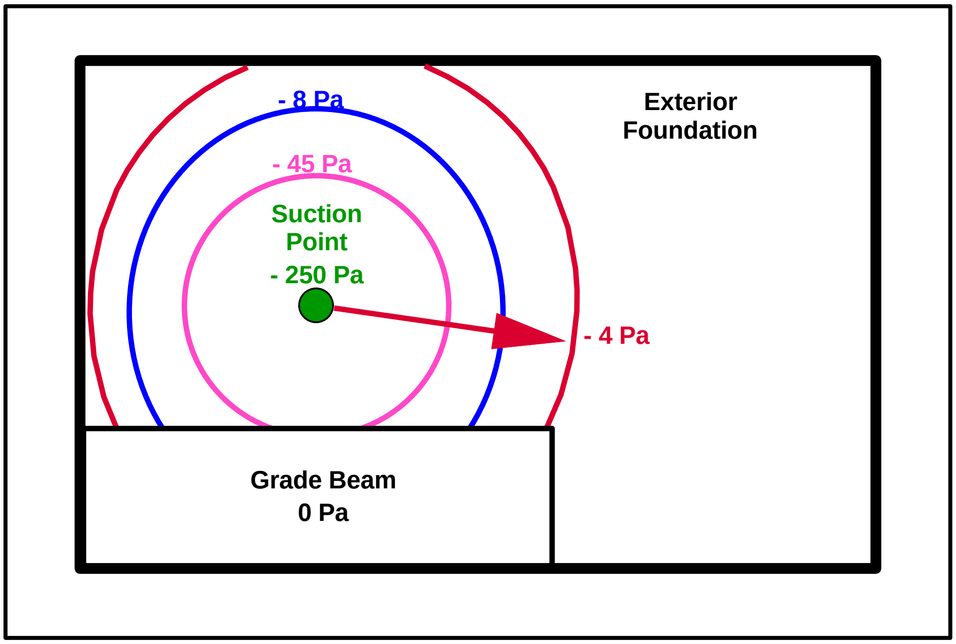


Figure 71. Impact of grade beam on ROI.

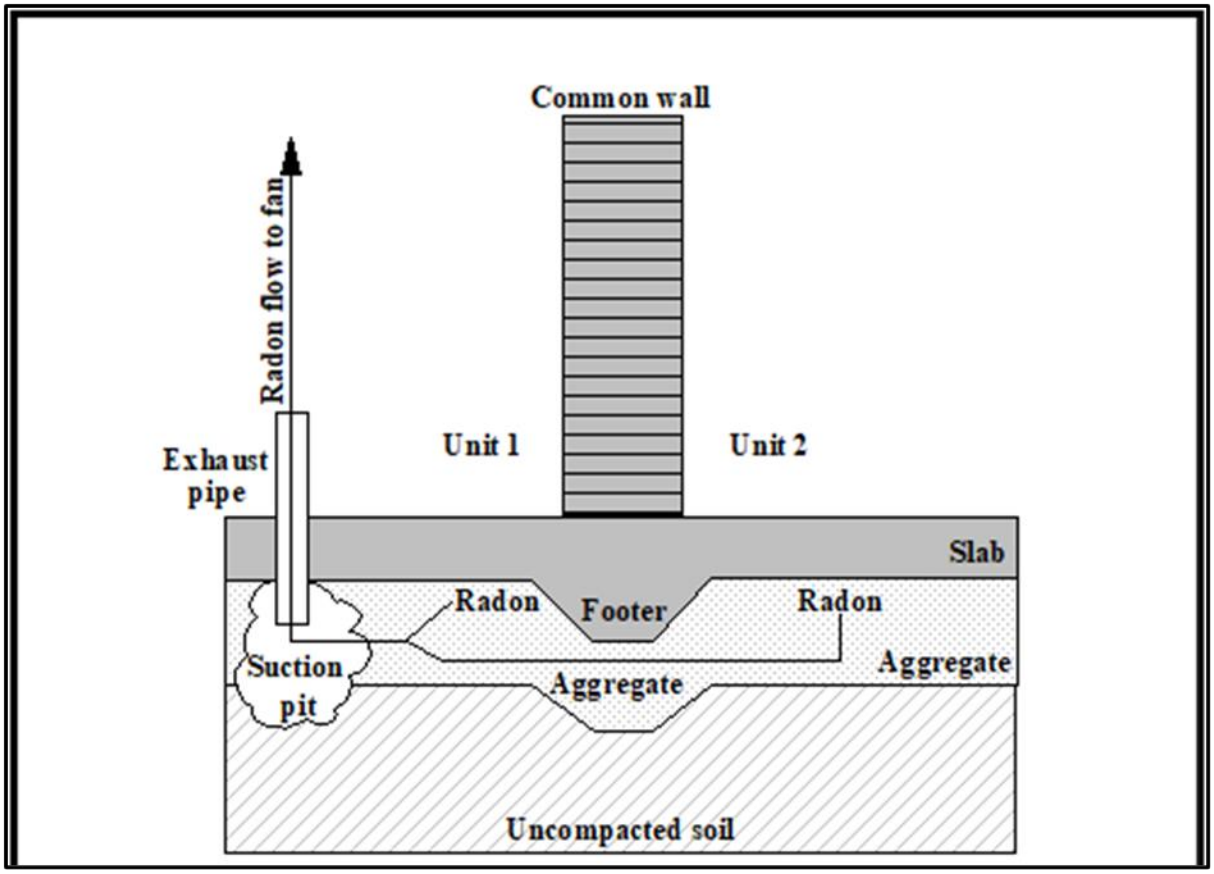


Figure 72. Gravel under a grade beam.

7.3.3 Aggregate Type and Depth and Vapor Barrier

One of the most critical components of any RRNC system is the aggregate base. The higher the permeability, the greater the radius of influence (ROI) for a given radon vent pipe. Studies have found that a minimum of 4 in. (6 to 8 in is preferred) of noncompacted ASTM C33 requirements for size numbers 5, 6, 56, or 57 provide optimum permeability. For best results, the aggregate should have a high percentage of ¾ in. stone with < 5 % fines. Unimpeded coverage using this uncompacted stone and a soil gas collector (Section 7.3.6) typically provides upwards of 4,500 ft^2 of coverage for a 4 in. exhaust riser and up to 10,000 ft^2 for a 6 in. exhaust riser. Exhaust risers that are 3 in. in diameter although allowable under the standards are not recommended because of the reduction in coverage (up to 2,500 ft^2) and potential exhaust noise if the system is activated.

At installations where aggregate is not available, sand or native soil may have to be used. It is important that the sand or soil selected must have hydraulic conductivity. Sands that contain 10% or more of fine sand, silt and clay are impermeable and not suited for this application. Because of low permeabilities found in sand and soils, a geotextile drainage matting will have to be installed. As a minimum the geotextile matting shall be at least 12 in. wide and placed between 12 to 18 in. along the entire perimeter of the foundation. The matting needs to be installed to allow for the lateral flow of soil gas from the soil gas collector to the suction point. For slabs > 2500 ft^2 it is recommended that additional geotextile matting be placed at 20 ft. intervals along the long side of the slab (Figure 73) to ensure good coverage. Additional information on this topic can be found in CC-1000.

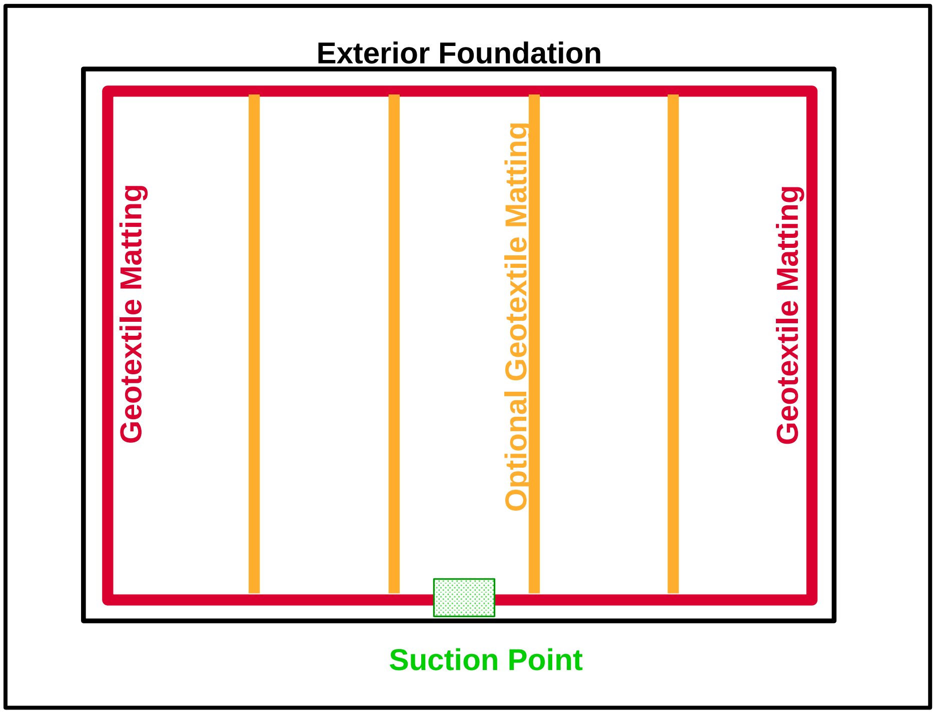


Figure 73. Geotextile matting with optional cross branches in sand or soil.

Within buildings with slabs, all RRNC systems must have a vapor barrier installed (minimum 6 mil or 3 mil cross-laminated) with 12 in. seam overlaps. It is important to note that the plastic vapor barrier is not “radon proof”. However, it does help reduce the radon flux through the slab into the living area. The primary purpose of the vapor barrier is to prevent wet concrete or water with concrete fines from getting into the aggregate or sand/soil layer or the geotextile matting. If concrete does permeate the aggregate or sand/soil layer or geotextile matting the ROI will be reduced.

7.3.4 Vent Pipe Routing

Under NAVRAMP, the installation has the option to choose a mitigation ready or a mitigation rough-in RRNC system. A mitigation ready system only requires the installation of a radon fan and a performance indicator for activation. The proposed electrical service for the fan is located near the fan (must be within 6 ft. for proposed attic mounted fans). The vent pipe is inserted through the slab into the aggregate bed (must have a tee on the bottom of the pipe) or connected to a soil gas collection plenum. The pipe can then be routed through the interior of the building to 1 ft. above the roof or can be routed to the outside of the building. It is important to note that if vent pipe is routed through the interior of the building to above the roof, the radon fan will have to be mounted within the attic or on the roof (a radon fan cannot be mounted within or below a lived-in or occupied areas). Therefore, attic or roof access will be required to install the fan and to perform system inspections and future fan replacements. To perform these tasks ladders or a high lift will be required and depending on the circumstances, a fall protection plan. On the other hand, if the vent pipe is mounted on the exterior of the building the fan can be mounted at waist height (35 to 45 in. above grade) negating the need for ladders or a high lift for fan installation and replacement. In addition, all roof penetrations have the potential to leak. Exterior pipe runs do not need to penetrate the roof thus eliminating the potential for water leaks in the future. For mitigation ready RRNC systems, the vent pipe exhaust port should not be capped but instead be open to the atmosphere and equipped with either a rain cap or wire mesh rodent/insect screen not smaller than ½ in. mesh. This mitigation ready design is commonly referred to as a passive stack RRNC system (Figure 74).

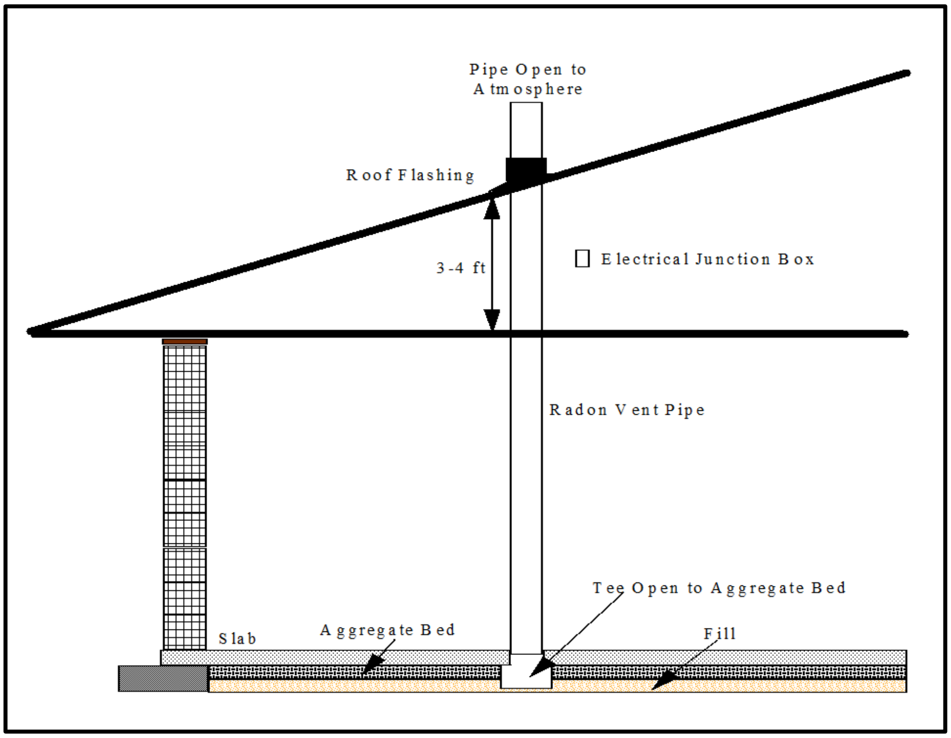


Figure 74. Example of a mitigation ready RRNC system.

Mitigation rough-in on the other hand will require, in addition to the installation of the radon fan and performance indicator, the installation of pipe if activation is required. Like the mitigation ready design, the vent pipe is inserted through the slab into the aggregate bed (must have a tee on the bottom of the pipe) or connected to a soil gas collection plenum. The vent pipe is then terminated with a cap on either the interior or exterior (preferred) of the building (Figure 75). An alternate for exterior stub outs (do not use on interior stub outs) is to use a screened goose neck (Figure 76). The electrical junction box connected to a dedicated circuit (Section 7.3.7) is installed within 6 ft. of the proposed fan location. It is important to note that in all mitigation rough-in designs the vent pipe must be capped, equipped with a screened goose neck, exposed (e.g., not buried below grade or under the slab), totally accessible and of sufficient length (minimum of 4 in.) to allow for the installation of additional pipe if activation is required. Actual examples of inaccessible locations are:

- Behind the HVAC blower unit
- Within the attic eve with < 1 ft. vertical clearance
- A stub out located on the building's sidewalk or buried under the parking lot, and
- Inside an enclosed, finished wall

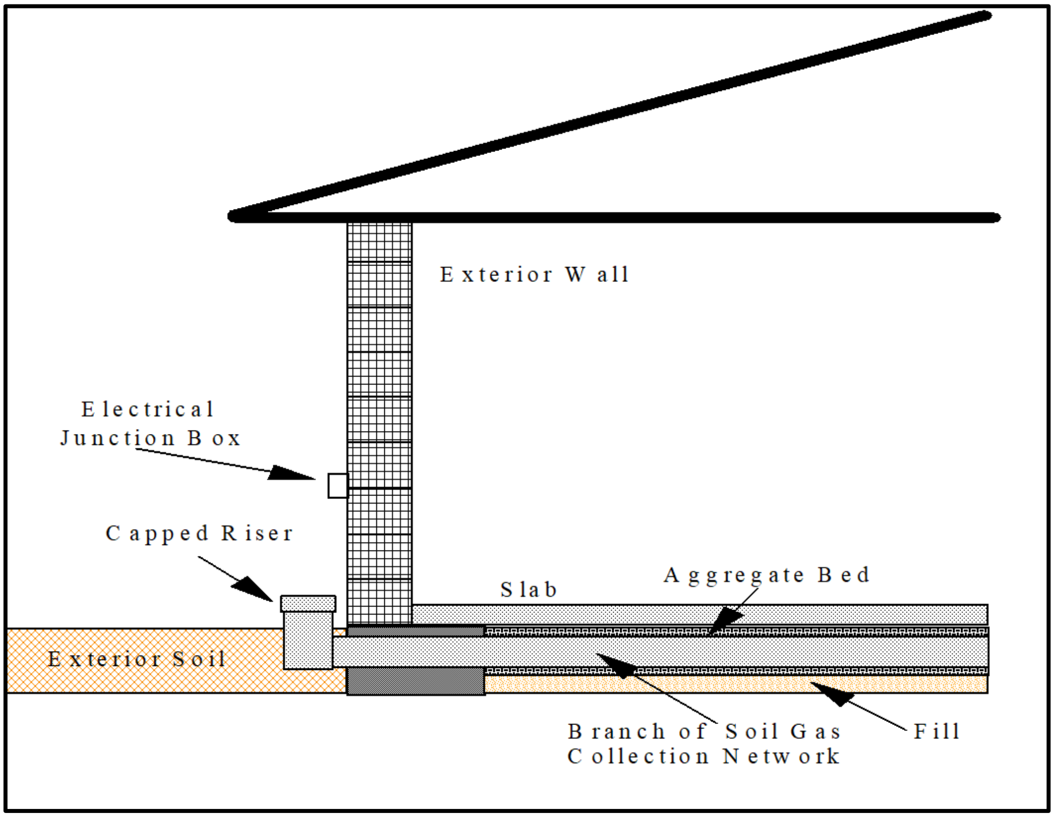


Figure 75. Example of a RRNC mitigation rough-in system.

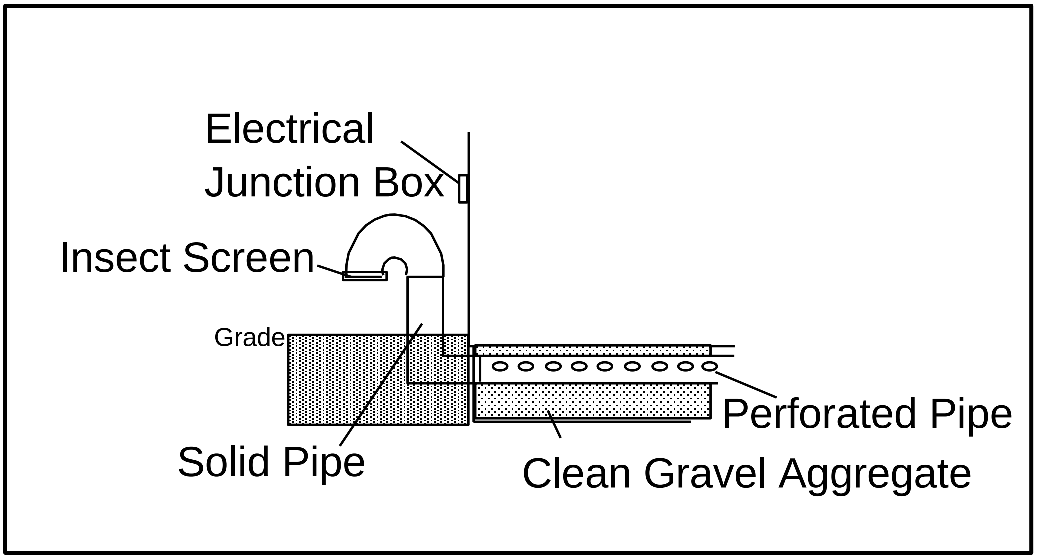


Figure 76. Mitigation rough-in with optional screened goose neck.

Based upon durability studies in Navy and USMC buildings, all vent pipe should be either solid or foam core 4 or 6 in. SCH 40 PVC pipe (see ASTM D4396 – 15) and shall comply with ASTM D2665, F891, or F1488. All fittings used in the vent pipe shall be SCH 40 PVC and compatible with the pipe. The joint surfaces for PVC plastic pipe and fittings are to be solvent welded (ASTM D 2564) and prepared with a primer (ASTM F 656).

If a soil gas plenum has been installed, the connection from the plenum to the vent pipe must be air-tight and made using a fitting designed for the transition from the plenum pipe to the vent pipe. Connections like the one shown in Picture 36 reduce the effectiveness of the RRNC system and will draw in conditioned air if activated.

Picture 36. Example of a noncompliant RRNC system connection.

For larger buildings, the installation of multiple risers will be required. The number and location of them will be determined by many factors. For example, for slabs with the appropriate depth of noncompacted permeable gravel with no subslab impediments to vacuum field extension, one riser for slabs up to 2,500 ft^2 would be adequate. However, for larger or more complicated slabs, it is recommended that a soil gas collection plenum be installed (Section 7.3.6) to enhance the coverage for each riser. Briefly a soil gas collection plenum is a network of perforated pipes in or below the aggregate bed that is connected to the vent pipe. In certain configurations, the coverage from one riser can be as high as 10,000 ft^2. Additional information on soil gas collection plenums can be found in CC-1000, CCAH-2020 and Section 7.3.6.

7.3.5 Proposed Fan Location and RRNC System Activation

The problem with current standards passive stack design, is that the fan (if required), has to be mounted in either the attic or on the roof of the building (See Type 3 SSDs, Figures 29 and 30). For private property owners this is not that much of an inconvenience to inspect or repair one or two SSD systems. But, at some naval installations there are over 300 SSD systems to inspect and maintain. Radon fans that are located in an attic or on a roof require considerably more time to inspect and repair. In addition, to perform these tasks ladders or a high lift will be required and depending on the circumstances, a fall protection plan. On the other hand, if the vent pipe is mounted on the exterior of the building the fan can be mounted at waist height (35 to 45 in. above grade) negating the need for ladders or a high lift for fan installation and replacement. In addition, all roof penetrations have the potential to leak. Exterior pipe runs do not need to penetrate the roof thus eliminating the potential for water leaks in the future if system activation is never required. From a maintenance perspective, studies performed at naval installations have found that Type 1 and Type 2 SSD systems built to NAVRAMP specifications (Section 4.3.2) with the fan mounted between 35 to 45 in above grade can be inspected in under 5 minutes and the fan replaced in 15 minutes or less. However, Type 3 SSDs could take well over an hour for inspection if fall protection and other safety measures are required.

Radon fans can only be mounted in unconditioned space and cannot be mounted below a lived-in area. If the attic space is used as a return air plenum or it is an unvented space, the standards require that the fan be enclosed and isolated so that it does not communicate? with the attic space. In addition, the enclosure must have a passive vent connected to the outdoors with at least 25 in^2 of opening. In addition to this requirement, NAVRAMP also recommends:

For attic mounted fans:

- The proposed fan location(s) must be within 30 ft of the attic opening.
- The opening to the attic shall be at least 22 in. X 30 in.

- A permanent walkway from the attic opening to the proposed fan location be installed.
- A permanent working platform (minimum of 24 in. x 24 in.) for the fan installer or maintenance worker be placed near the fan.
- The clearance provided for fan installation/replacement shall have at least 36 in of vertical height centered directly above the vent pipe and have a horizonal cylindrical space around the center of the pipe of at least 21 in.
- The electrical outlet should be located within 6 ft of the proposed fan location.

For roof mounted fans:

- The fan needs to be mounted a minimum of 6 ft off the edge of the roof.
- It is recommended that the roof be no more than a 9/12 pitch.
- If required, install a permanent tie off for fall protection equipment on the roof near the fan.
- All fans must be installed using a support structure which attaches to the vent pipe above the fan.
- The electrical junction box should be located within 6 ft of the proposed fan location.

For exterior wall mounted fans:

- The fan should be mounted ideally between 35 in. to 45 in. above grade.
- The electrical junction box should be within 6 ft of the proposed fan location.

In recent years there has been some debate on activating all RRNC systems upon building completion. The key assumption being that within an EPA Radon Zone 1 (Figure 4), the odds of having elevated radon are significant. The key concern being that testing would not be performed prior to occupancy and that people could live or work within a building for decades without knowing that elevated radon was present. However, under NAVRAMP, radon testing prior to occupancy is recommended and retesting of the building at an RPC 1 installation or site is performed every 5-years. Therefore, the radon exposure concern is not warranted. Although the cost of activating and RRNC system prior to occupancy is not that excessive, the cost of operating, inspecting and maintaining an active SSD system for the lifetime of the building is. In addition, studies at installations with the highest radon levels and greatest frequency of elevated radon within the Navy and USMC has determined that if all of the buildings had had RRNC systems, only 20% of the systems would have needed to been activated. Therefore, under NAVRAMP, the RRNC systems should only be activated if elevated radon is present.

7.3.6 Soil Gas Plenum

Because of the permeability limitations of gravel (up to about 2,500 ft^2 of slab area), soil gas plenums (SGP) are routinely installed to enhance and extend the vacuum field under the slab. Briefly speaking the SGP is a loop or network of perforated pipe placed within the aggregate base or buried within a trench which extends some distance away from the vent pipe. The SGP is then connected to the vent pipe either directly or via a minimum 5-gallon subslab pit (Figure 77). SGP can be configured into a grid (Figure 78) or in a loop configuration (Figure 79). For buildings with grade beams or other structural impendences to vacuum projection, an SGP can provide coverage for these areas which would typically require their own vent pipe (Figure 80). Depending upon the requirements and design, the SGP can be either SCH 20 or SCH 40, 4 in. or 6 in. perforated PVC or polypropylene pipe. Based upon past experience, the use of 3 in. pipe in high flow SGP is not recommended.

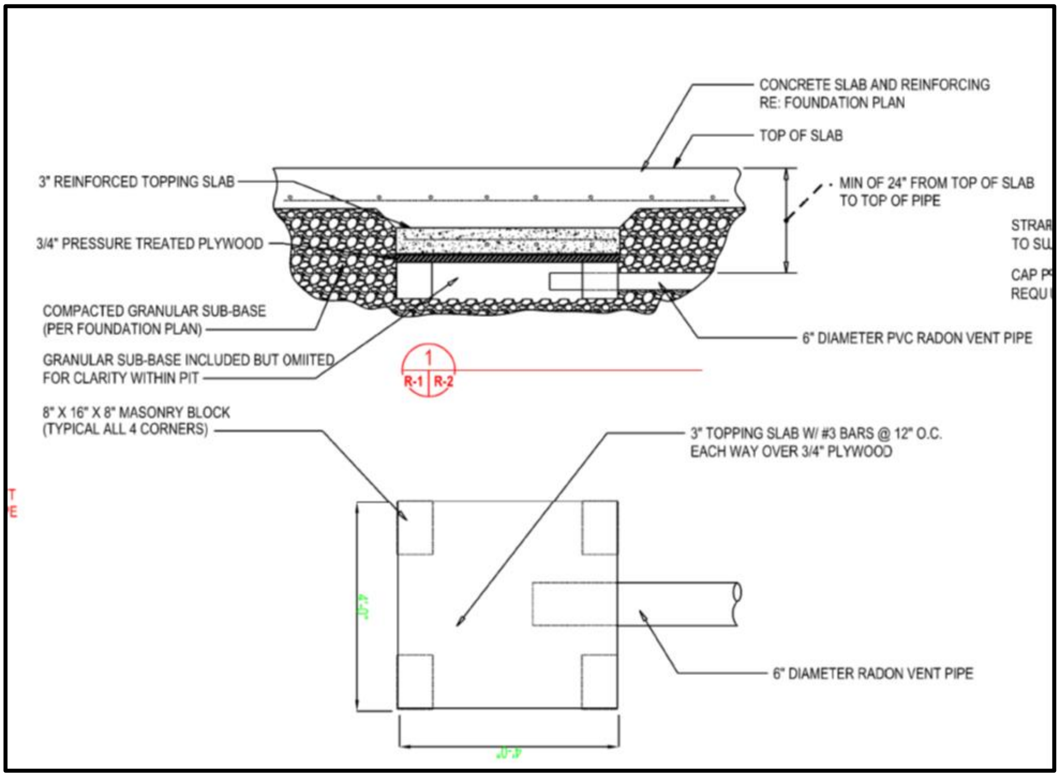


Figure 77. Example of a soil gas collection suction pit.

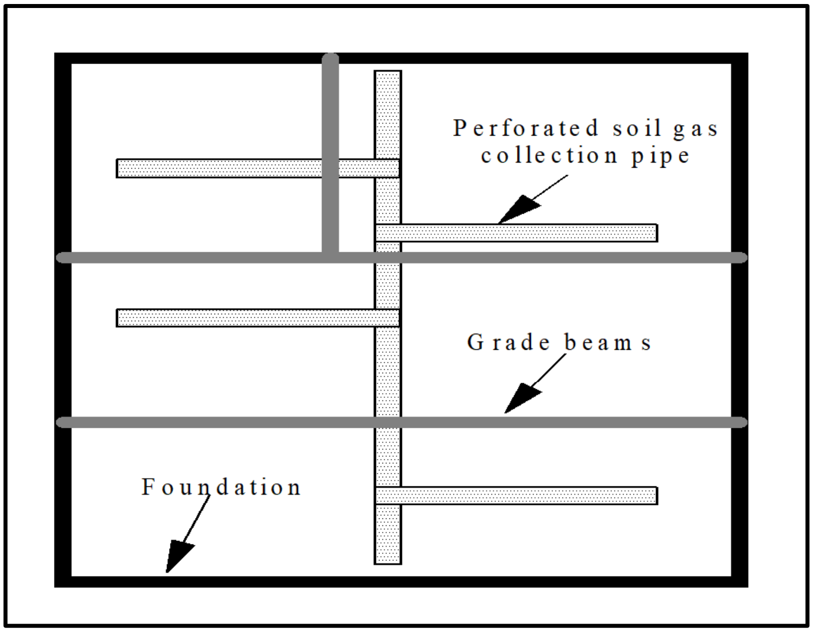


Figure 78. Example of a grid soil gas collection plenum.

For slabs < 2,500 ft^2 which have no grade beams or other impedance to vacuum field projections, the installation of an SGP is optional for noncompacted 6 to 8 in. of ASTM C33 size numbers 5, 6, 56, or 57 gravel is used. ROI studies within naval buildings has found adequate vacuum field extension in all cases for this specific condition. However, similar sized buildings with a simple 4 in. corrugated loop did have 30% greater vacuum. For larger slabs > 2,500 ft^2 an SGP in combination the correct gravel (Section 7.3.3) can extend the coverage for each vent pipe considerably. For example, a 4 in. vent pipe connected to a 4 in. SGP can cover up to 4,500 ft^2 of slab and a 6 in. vent pipe connected to a 6 in. SGP can cover up to 10,000 ft^2. For larger buildings, multiple risers connected to independent SGP are typically installed (Figures 79 and 80). It is recommended that multiple risers with SGP not be physically interconnected, but some overlap of the vacuum field from each SGP is encouraged.

The perforated pipe can be installed using one of two methods. The simplest method is to place the pipe in the aggregate bed (Figure 81). It is recommended that the corrugated pipe not be placed directly on the soil but on a minimum of 2 in. layer of gravel and covered with at least 2 in. of gravel (Section 7.3.3). Therefore, for a 4 in. perforated pipe the gravel bed would need to be 8 in. in thickness. Another option is to place the corrugated pipe within a trench (Figure 81, Picture 37). The trench needs to be a minimum of 8 in. wider and 4 in. deeper than the outer diameter of the pipe. The advantages of the trench installation are that it is more resistive to being crushed during construction and has superior water drainage.

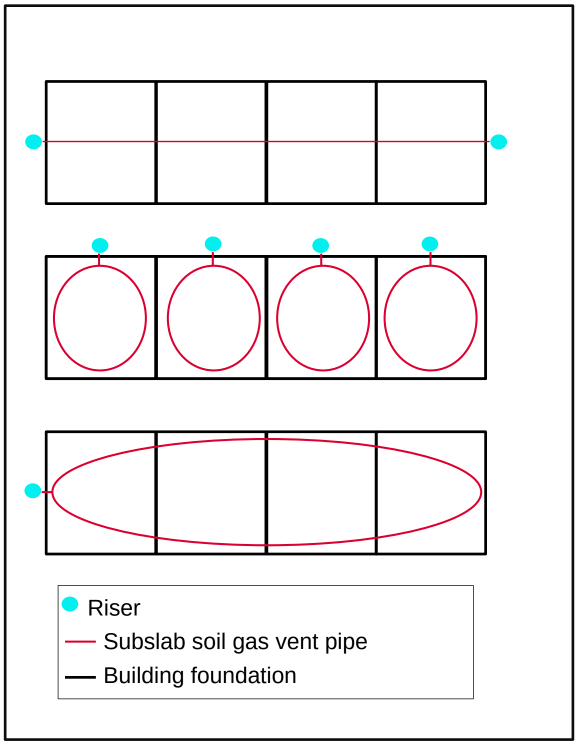


Figure 79. Example of a soil gas collection system using flexible drain pipe.

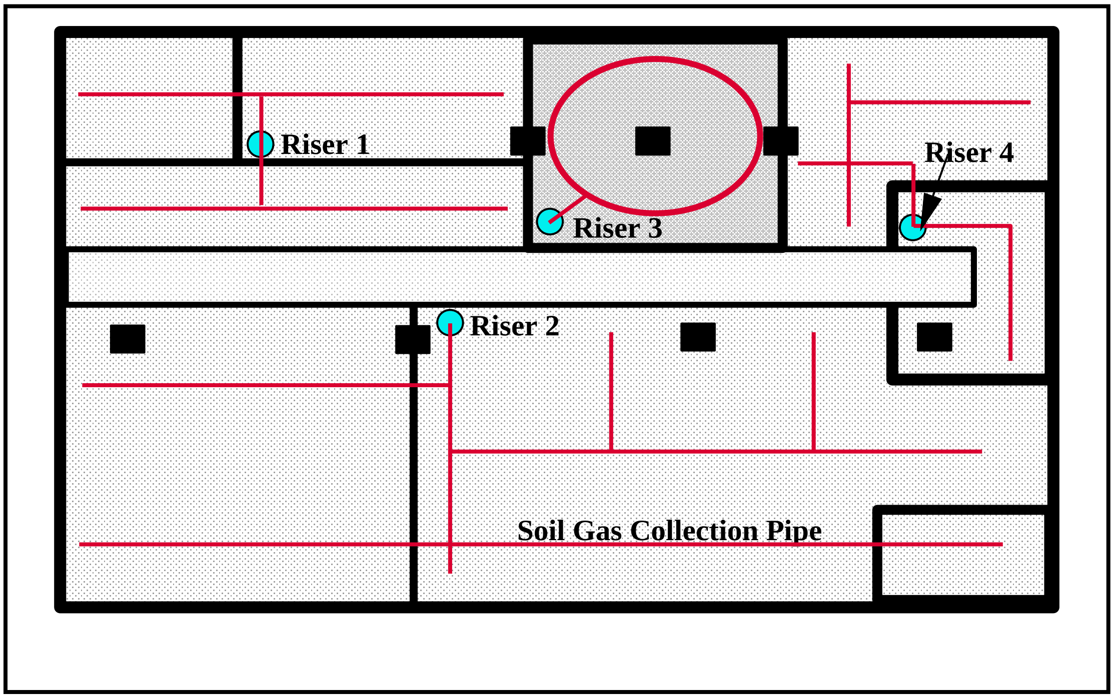


Figure 80. Example of multi-riser soil gas collection network

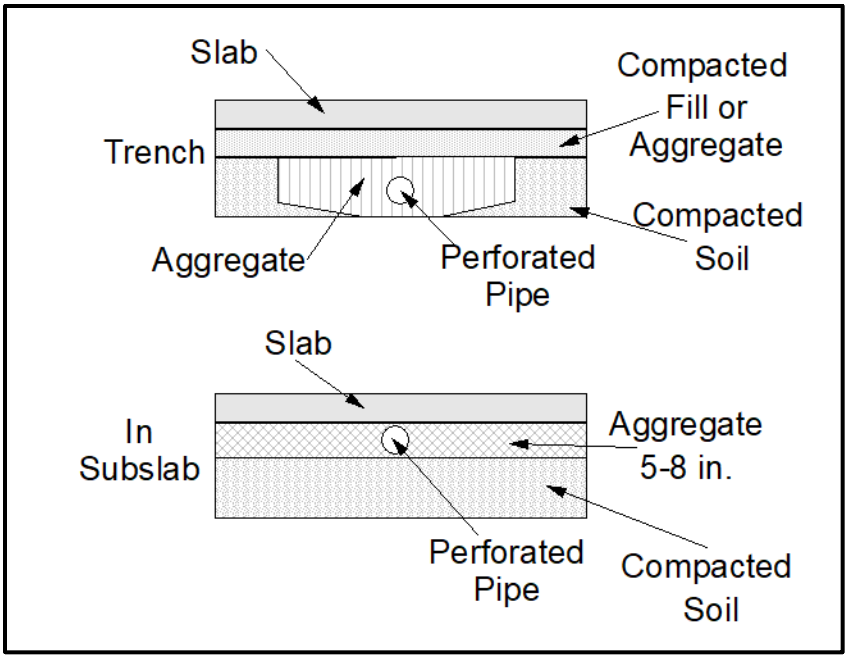


Figure 81. Soil gas plenum options.

Picture 37. Buried perforated pipe.

Because of structural and seismic reasons, in some buildings the use of smaller grain, higher fine, compacted aggregate must be used. In these cases, geotextile matting is placed under the vapor barrier directly on top of the compacted aggregate. Like in sand or compacted soils (Section 7.3.3) the geotextile matting must be at least 12 in wide and placed between 12 to 18 in. along the entire perimeter of the foundation (Figure 73). The matting needs to be installed to allow for the lateral flow of soil gas from the soil gas collector to the suction point. For slabs > 2500 ft^2 it is recommended that additional geotextile matting be placed at 20 ft intervals along the long side of the slab (Figure 73) to ensure good coverage. Additional information on this topic can be found in CC-1000. Another option is to install an SGP network within a trench with branches no more than 20 ft apart. The SGP network can then be covered with more permeable gravel (Section 7.3.3) and then the compacted structural/seismic aggregate base applied on top of the SGP trench.

In summary, the installation of an SGP coupled with the correct aggregate has an extremely high success rate in the private sector if activation was required. Within naval installation, the success rate with properly designed and sized SGP, aggregate, and vent pipe is 100%. In most cases, radon mitigation diagnostics is not required for buildings equipped with an RRNC-SGP network. Because the RRNC system is already present, design and other SSD rough-in considerations and costs are not required as well. In addition, if the system is located on the exterior of building, interior access requirements would be minimized.

7.3.7 Electrical Service for Fan Activation

In SSD mitigation installations, one of the more significant potential costs is electrical. The industry mitigation standards and the National Electric Code (NEC) requires that a radon fan must not be more than 50% of the circuit capacity and not be connected to a circuit that would exceed 80% (including the radon fan) of the circuits rated capacity. If power sources near the SSD system cannot meet these requirements, then a new, dedicated circuit would be required. For this reason, it is recommended that all RRNC systems have a dedicated circuit in the panel. Multiple fans can be powered by the same circuit provided they do not total to ≥ 50% of the rated circuit capacity. In addition, the junction box for the proposed fan should be within 6 ft of the proposed fan location. It is important to note that attic mounted fans can have a corded connection provided they are within 6 ft of the outlet. Fans mounted on the exterior of the building must be hard wired and use components that are suitable for wet locations. If activation is required, to facilitate maintenance and reduce the inconvenience to the residents or occupants it is recommended that a switch be installed within 3 ft of the fan. Having the switch at this location would not require lock-out tag out procedures and having to de-energize the circuit prior to replacing the radon fan.

Additional requirements include the following:

- The radon fan circuit must be a properly ground circuit.
- Wiring may not be located in or chased through the mitigation installation ducting or any other heating or cooling ductwork.
- To facilitate fan replacement, the switch for the radon fan should be located within 3 ft of the fan.

    - Disconnect switches are not required for plugged fans.
- All wire shall be solid, 12 AWG (UFGS-31 21 13, 2018).

7.3.8 Sealing of the Slab

To ensure optimal performance of the RRNC system, to the best extent possible, the slab must be sealed to prevent soil gas entry and loss of conditioned air if system activation is required. Common examples of items to seal are cold and expansion joints, openings around plumbing and electrical penetrations, structural piers and other openings and penetrations between the slab and the soil. Gaps can be filled with polyethylene backer rod or comparable filler material as required and sealed with polyurethane caulk or other types of elastomeric sealant. Caulks and sealants shall be applied according to the manufacturer's instructions. Sealing coupled with a soil gas collection system and vent pipe to the atmosphere provides a low path of resistance to allow radon soil gas to escape passively to the atmosphere. In addition, if system activation is required, a properly sealed slab in most cases will require a less powerful radon fan which will help reduce activation cost and will save on energy.

The current industry RRNC standards (Table 15) provides a list of common items that requiring sealing and sealant recommendations. Although outdated, additional information and design drawings can also be found in (ASTM E1465-08a [ASTM 2008, withdrawn in 2017], or UFC 3-490-04A, inactive with no replacement [UFC May 2003]).

7.3.9 RRNC Performance Verification

After the concrete floor has been poured and adequate time allowed for curing, it is recommended that a performance check be done on the vent pipe network to confirm that the expected coverage with the proposed fan was met. To complete the test, the proposed mitigation fan is temporarily installed on the riser, activated (not hard wired) and the resultant vacuum measured at the most distance points of the subslab vent pipe grid. These test holes must be uniquely numbered and identified on an eye-perfect or to-scale floor or foundation plan. The differential pressure for each test hole (typically 3/8 in.) is then recorded on a data form or on the building floor or foundation plan. Minimum acceptable vacuum would be -2 Pa or -0.008 WC. In cases where the minimum is not met, a higher flow or suction fan should be tried and the vacuum remeasured. If the minimum vacuum cannot be established then additional test holes will be required to locate the -2 Pa or -0.008 WC contour. The graphic contour on a floor or foundation plan or the distance of the radius of influence from the suction point shall then be provided in the as-built drawings (Section 7.3.10).

7.3.10 Documentation for an RRNC System Design

Studies conducted at naval installations has found that although newly constructed buildings can have elevated radon levels, a significant number of homes and nonresidential buildings develop radon issues years or even decades after construction. The problem with older RRNC systems and designs has not been their effectiveness in reducing radon levels after activation, but knowing that they were present in the building. In some cases, the RRNC system was discovered during or after SSD installation had been completed. In these cases, the RRNC-system plans were either omitted in the as-built drawings or were integrated into the buildings plumbing plan and not properly identified. RRNC vent pipes exiting the roof are very similar in appearance to plumbing vent pipes and can only be identified in the absence of building plans by performing SSD diagnostics.

This problem is not unique to the Navy and USMC, it also is prevalent in the private sector as well. In one noted example, during a renovation, a plumber connected a sanitary drain pipe to the RRNC vent pipe resulting in flooding in the basement. Because of this and other instances the current RRNC standards (Table 15) have mandatory labeling requirements for all RRNC vent pipes.

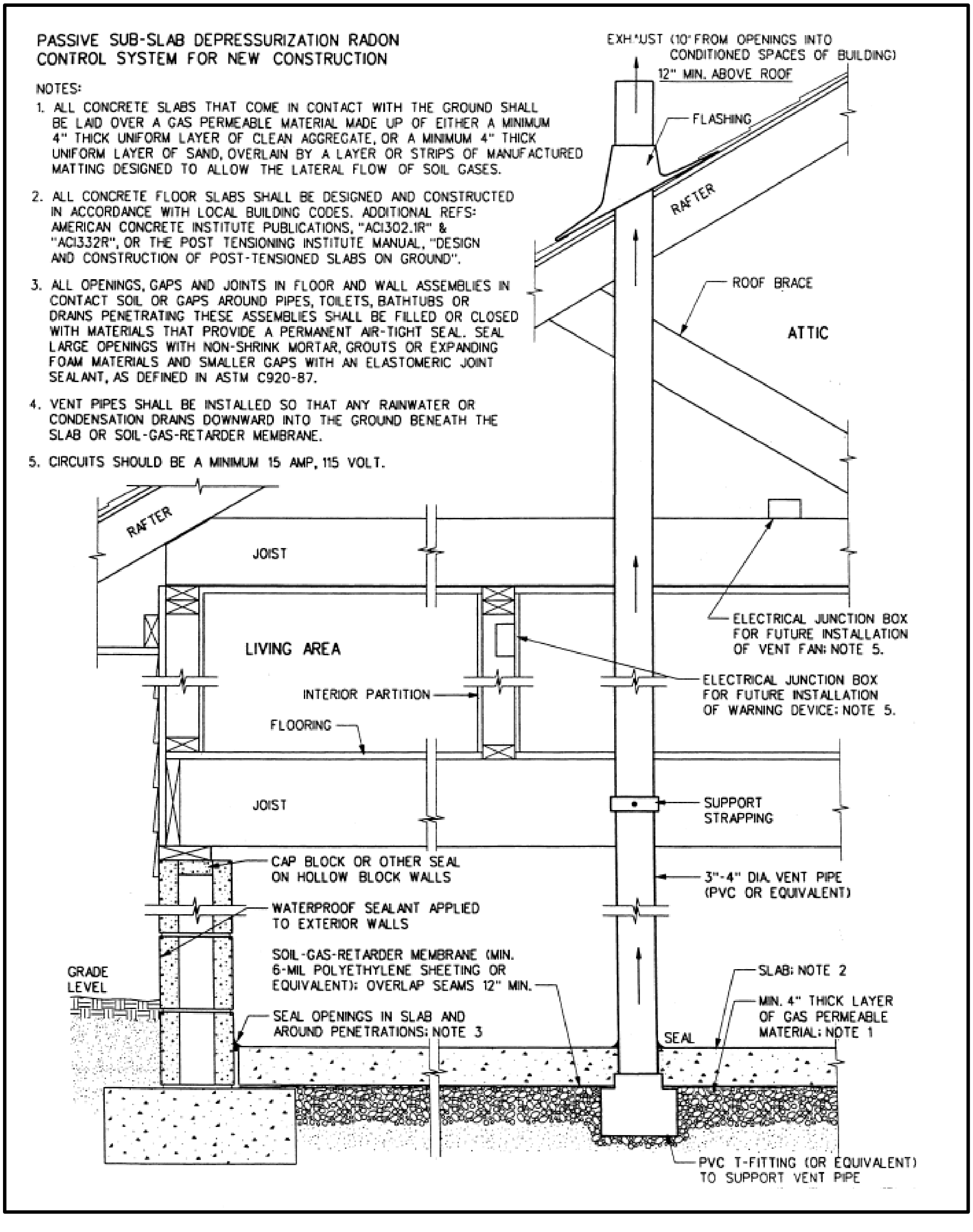
Under NAVRAMP, system components shall be labeled as specified in ANSI/AARST CCAH 2020 for all passive stack and mitigation-ready options. This would include but not be limited to labels that identify the vent piping as part of a radon reduction system in visible, inside walls and attics. As a minimum all system lettering shall be not less than ¼ in. in height and shall be of a color in contrast to the background color to which the lettering is applied. The label shall state “Radon Reduction System” and if applicable a unique system identification number. Optional information may include the installers name and certification number, date installed and the contract number. At the proposed fan location, a label shall state “Location of Radon Fan” along with the system number, electrical panel and circuit number. In the electrical panel, the circuit breaker shall be labeled Radon Fan and shall include the system number.

In addition, a label or placard stating the building contains an RRNC system shall be permanently placed in a visible, eye level location in the mechanical room. If the building does not have a mechanical room, it can be placed in a janitor closet, electrical or communication closet, or a bathroom. As a minimum the label shall be at least 4 in. height and width and shall have a color in contrast to the background color to which the lettering is applied. The label shall state “RRNC System Information”, which method for RRNC was used and the location of the riser and/or stub outs and include recommended mitigation fans for each system if activation is required.

For buildings in which RRNC systems have been incorporated, the as-built drawings must have a section labeled “RRNC System Design”. Within the RRNC system design section the following must be included:

- To scale drawings of
  - Soil gas collection plenum
    - If more than one vent pipe riser is present, they shall each be assigned an easy-to-follow identifier (e.g., Riser 1, Riser 2 etc.)
  - Cross section of the soil gas collection plenum trench
  - Cross section of the soil gas collection plenum and radon vent pipe (e.g., suction pit details)
  - Plumbing plan for the vent pipe riser from the suction point to the exhaust location including proposed fan location and electrical service
  - If applicable, roof flashing details for the vent pipe
- In the notes section the following shall be documented:
  - Declaration if the installed RRNC system is a mitigation ready or a mitigation rough-in installation
  - Specifications for all parts used in the RRNC system if not documented in the drawing including trench backfill and the gas permeable layer aggregate
  - A list and specifications for all parts required to activate the radon mitigation system
  - The electrical panel and breaker number for each proposed fan
  - Section callouts for all slab sealing
  - If applicable the findings of the RRNC performance check (Section 7.3.9)

Figures 82 through 84 are examples of acceptable RRNC-system drawings.



PASSIVE SUB-SLAB DEPRESSURIZATION RADON CONTROL SYSTEM FOR NEW CONSTRUCTION

NOTES:

1. ALL CONCRETE SLABS THAT COME IN CONTACT WITH THE GROUND SHALL BE LAID OVER A GAS PERMEABLE MATERIAL MADE UP OF EITHER A MINIMUM 4" THICK UNIFORM LAYER OF CLEAN AGGREGATE, OR A MINIMUM 4" THICK UNIFORM LAYER OF SAND, OVERLAIN BY A LAYER OR STRIPS OF MANUFACTURED MATTING DESIGNED TO ALLOW THE LATERAL FLOW OF SOIL GASES.
2. ALL CONCRETE FLOOR SLABS SHALL BE DESIGNED AND CONSTRUCTED IN ACCORDANCE WITH LOCAL BUILDING CODES. ADDITIONAL REFS: AMERICAN CONCRETE INSTITUTE PUBLICATIONS, "ACI302.1R" & "ACI332R", OR THE POST TENSIONING INSTITUTE MANUAL, "DESIGN AND CONSTRUCTION OF POST-TENSIONED SLABS ON GROUND".
3. ALL OPENINGS, GAPS AND JOINTS IN FLOOR AND WALL ASSEMBLIES IN CONTACT SOIL OR GAPS AROUND PIPES, TOILETS, BATHTUBS OR DRAINS PENETRATING THESE ASSEMBLIES SHALL BE FILLED OR CLOSED WITH MATERIALS THAT PROVIDE A PERMANENT AIR-TIGHT SEAL. SEAL LARGE OPENINGS WITH NON-SHRINK MORTAR, GROUTS OR EXPANDING FOAM MATERIALS AND SMALLER GAPS WITH AN ELASTOMERIC JOINT SEALANT, AS DEFINED IN ASTM C920-87.
4. VENT PIPES SHALL BE INSTALLED SO THAT ANY RAINWATER OR CONDENSATION DRAINS DOWNWARD INTO THE GROUND BENEATH THE SLAB OR SOIL-GAS-RETARDER MEMBRANE.
5. CIRCUITS SHOULD BE A MINIMUM 15 AMP, 115 VOLT.

Figure 82. Example architectural drawings for an RRNC system.

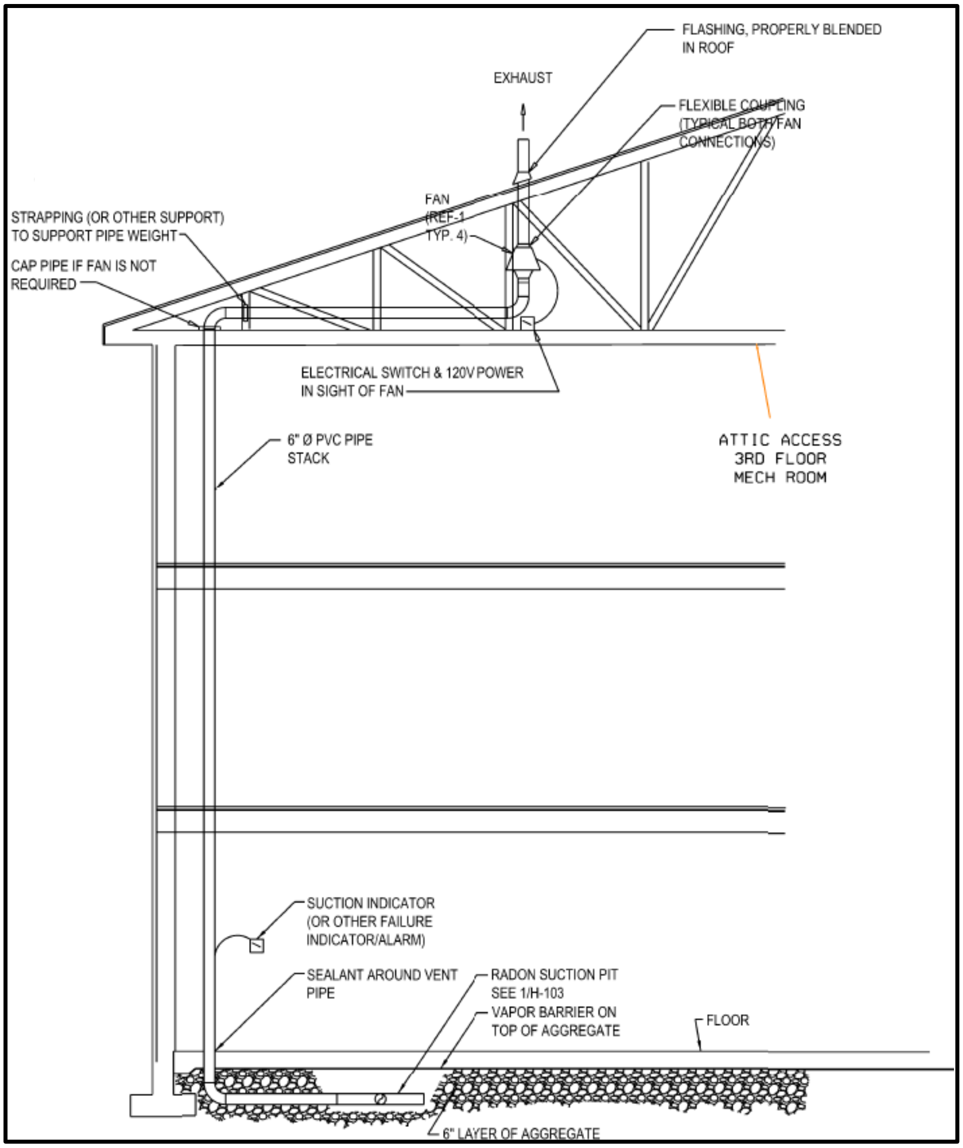


Figure 83. Example of a documented RRNC system design.

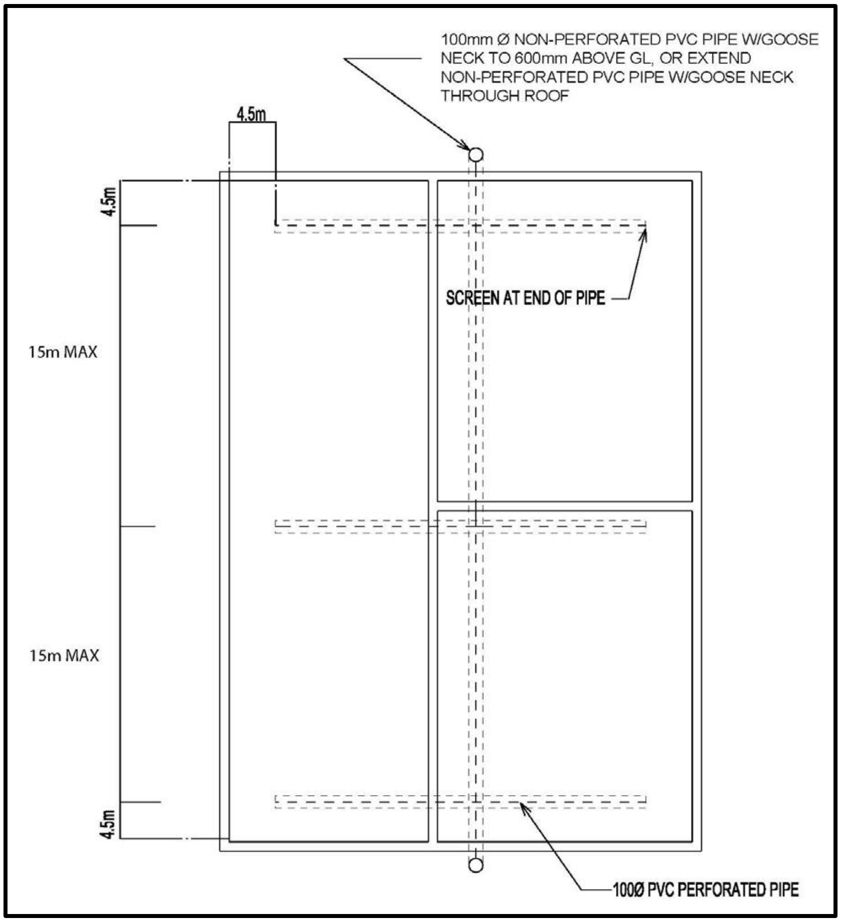


Figure 84. Example of soil gas plenum design.

7.4 ROLE OF THE BUILDING MECHANICAL SYSTEMS IN RRNC

Another RRNC technique in residential and nonresidential construction, which supplements the techniques mentioned previously, is to design the building mechanical systems so that all the rooms in ground contact are pressurized relative to the subslab (ASHRAE 2010, *Indoor Air Quality Guide*, Section 3.3). Although no standard has been proposed for how much pressure is needed, studies by DOE have found 4 Pa (0.016 WC) sufficient for consistent radon control. Another option is to allow for additional ventilation in the ground-contact rooms in the design. However, the inability to predict in advance what the radon levels might be within those rooms limits the application of this technique.

8. RADON TRAINING AND CERTIFICATIONS

Under EPA testing and mitigation guidelines for implementation of the IRAA, government employees and military personnel may perform the radon testing and mitigation at their facilities without certification, although accredited radon testing and mitigation training is recommended. However, installation contractors [e.g., Base Operations Support (BOS), Indefinite Delivery/Indefinite Quantity (IDIQ) or similar] or their subcontractors must meet all the contractor requirements listed above. Under NAVRAMP, if uncertified government employees and military personnel are going to be utilized for radon testing or mitigation at an installation, the installation must decide if training and certification is required to meet the needs of their radon program. It is important to note that the accredited testing and mitigation training being offered under the auspices of NRPP or NRSB does not address the logistics and problems which occur during large testing and mitigation projects.

It is important to note that classes and exam being offered by NRPP and NRSB are not interchangeable. Therefore, a decision is required as to which certifying body the installation staff will be accredited by. NAVRAMP considers both acceptable. Both organizations offer different types of certifications (Table 16) depending upon the type of work being performed. All the classes for the various certifications are available on-line. At the conclusion of each training model the passing of an on-line proctored exam is required. With respect to mitigation certifications, both require a field competency demonstration overseen by an approved mitigation specialist or provider. Additional continuing education classes on different topics and certifications are also offered. For example, NRPP has additional certifications offered for multi-family housing testing and mitigation, large building testing and mitigation and RRNC. To obtain a mitigation certification, both organizations also require the completion of the testing course/exam.

As mentioned above, certification is not required by government employees and military personnel to perform radon testing or radon mitigation. However, the mitigation and RRNC classes can be taken without having a testing certification. Additional information on the certification process and a list of online classes can be found at:

https://www.nrsb.org/ or https://nrpp.info/certification/types-of-certification/

Table 16. Types of certifications offered

Genre	NRSB	NRPP
Radon testing	Radon Measurement Technician (8 h) Radon Measurement Specialist (16 h) Accredited Radon Laboratory (Demonstrated proficiency requirement)	Radon Measurement Field Technician (8 h) Radon Measurement Professional (16 h) Radon Measurement Professional with Analytical Services (Demonstrated proficiency requirement)
Radon mitigation	Radon Mitigation Specialist (24 h)	Radon Mitigation Installer (24 h)
RRNC design and installation	Not available at this time	RRNC (8 h)

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APPENDIX A: EPA CORRESPONDENCES

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UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

December 1, 2011

Mr. David Wilson
Research Staff
Oak Ridge National Laboratory/Sobran
115D Flint Road
Oak Ridge, Tennessee 38731

Dear Mr. Wilson:

This letter is in response to your recent request for additional information pertaining to radon and the testing intervals, action levels and standards, filtration, and radon-resistant new construction. EPA's understanding is that this information is pertinent to the NAVFACENGCOM effort to complete an update of the U.S. Navy's Radon Testing and Mitigation Guidebook.

Radon is a highly localized phenomenon. Identical buildings (or dwelling units within a building) that are adjacent to one another can have very different radon levels. Geologic and soil conditions, building design and materials, operation and maintenance, and the aging of the building are key variables that affect the radon concentration. Atmospheric conditions also play a significant role temporally in determining a building's radon concentrations. Buildings should be tested in accordance with the appropriate and approved protocol.

1-Testing Interval for Buildings or Spaces Not Mitigated. Homes that initially test below 4pCi/L should be retested periodically. In addition to the regular testing required by OSHA, EPA and the radon community of practice believe it prudent to test residential buildings every five years, consistent with current consensus standards of practice.[1] Furthermore, a radon test should be conducted following any activity with the potential to affect the air dynamic of any building. Changing a building's air flow dynamic has the potential to affect the radon concentration. For example, upgrading or replacing the HVAC system or windows, or adding a family room to the building.

2-Testing Interval for Mitigated Buildings. All buildings, once mitigated, should be tested within 30 days to confirm the mitigation system's initial effectiveness. Periodic testing should be conducted to confirm the continuing effectiveness of the mitigation system. More specifically, previously mitigated spaces in schools and other large buildings should be retested annually or every two years, consistent with current consensus standards of practice.[2]

3-Testing in New Residential Construction. Test for radon after the building is completed and all systems are operating properly, and prior to occupancy or the issuance of an occupancy certificate. In the case of passive radon mitigation systems, a radon vent fan should be added when the test result exceeds the EPA action level of 4 pCi/L.

4-Radon Action Level and Workplace Standards. For homes, including multi-family buildings, and schools, we recommend that these buildings be mitigated when the measurement or test result is 4pCi/L or more. If non-residential buildings are workplaces, they would be subject to the DOL-OSHA standard, i.e., the Maximum Permissible Concentration (MPC) of 100pCi/L for an adult worker's exposure in 40-hours over a consecutive 7-day period (work week). In addition, OSHA has posting (notice) requirements for radon concentrations below the 100 pCi/L standard.

[For details see http://www.osha.gov/dts/sltc/methods/inorganic/id208/id208.html, and http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=10098]

However, we strongly encourage you to consider a more protective approach to your workplaces. In Appendix A to its recent publication, *Indoor Air Quality in Commercial and Institutional Buildings* (OSHA 3430-04 2011), OSHA does note EPA's 4pCi/L action level. Presuming that the OSHA MPC is a minimum standard of protection, health & safety officers, and facility managers could as a matter of prudent policy choose to meet the more protective EPA action level.

5-High Efficiency Particulate Air (HEPA) Filtration. We don't recommend filtration or HEPA filtration as a radon control measure or mitigation technique. There is some evidence that filtration can reduce radon progeny concentrations. However, many factors can affect filtration's effectiveness in maintaining reduced progeny concentrations, including: (1) a potential increase in ultra fine particles available for progeny attachment and deposition in the lung; (2) a potentially larger percentage of progeny as an unattached fraction available to be deposited in the lung; (3) uncertainties with filter loading, consistency and cost of filter replacement, and maintaining a consistent air volume setting; (4) human interference with filtration device operation; and (5) the frequency (and cost) of radon progeny measurements needed to confirm that the desired progeny concentration is being maintained.

6-Pre-construction Radon Prediction. Soil flux measurements or measurement results from neighboring areas are not reliable methods for predicting a given building's radon level. Individual buildings should be tested in accordance with an appropriate and approved protocol.

7- Radon Resistant New Construction. We recommend that all homes, including multi-family buildings and schools, be built radon-resistant when located in high radon potential areas (Zone 1 on the EPA Map of Radon Zones). EPA also recommends that homes and schools built in medium radon potential areas (Zone 2 on the EPA Map of Radon Zones) consider using radon-resistant construction. Currently, the most appropriate standards are Appendix F of the ICC IRC, or ASTM E1465-08a.

We strongly encourage you to consider building non-residential buildings in accordance with a green building standard, e.g., the ICC International Green Construction Code (IgCC), or adapted from a closely relevant standard to offer occupants an increased level of protection from radon exposure and other health benefits. Please contact me (2020.343.9733, Long.Bill@epa.gov) or Phil Jalbert of my staff (202.343.9431, Jalbert.Philip@epa.gov) if you have questions regarding this letter.

Sincerely,

Bill Long

Bill Long, Director
Center for Radon and Air Toxics

cc: Philip Jalbert, EPA/ORIA/IED

[1] ANSI-AARST Protocol for Conducting Radon and Radon Decay Product Measurements in Multifamily Buildings (MAMF-2010; EPA 402-K-11-002).

2 MAMF-2010; EPA 402-K-11-002) - (see section II.G., page II:2.), and Reducing Radon in Schools: A Team Approach (EPA 402-R-94-008, April 1994) – (Section 9.1, page 9-1).

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UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460
Office of Radiation and Indoor Air
Indoor Environments Division

March 6, 2008

Ms. Teri Jamin, President
Douglas County School Board
1638 Mono Avenue
P.O. Box 1888
Minden, Nevada 89423

Dear Ms. Jamin:

Thank you for your letter of February 19, 2008 requesting assistance in answering questions posed by you and Ms. Luna with regard to the Zephyr Cove Elementary School (ZCES). We also received additional information from Mr. Greg Felton. He provided the minutes of the School Board Meeting (February 12, 2008) and a detailed email (March 4, 2008) on his observations and five questions related to radon risk. We normally refer such requests to our Regional offices. However, in this case, the EPA Region 9 office (San Francisco) has asked us to respond directly to your request.

Please be aware that this response is based only on the information we have received. Therefore, in the absence of complete information or a site inspection, we've limited our response to several general observations and recommendations. Our response addresses measurement, risk, mitigation and technical assistance. EPA's policies on radon measurement and mitigation are necessarily conservative and protective, and based on many years of research and experience in a wide variety of buildings, including schools. EPA's guidance on radon is a prudent and cost-effective long-term approach to risk reduction that is protective of students and staff alike.

Radon measurement. EPA's recommended action level has always been primarily defined as a radon gas measurement, i.e., 4 picocuries per liter of air (pCi/L). The Fallon report incorrectly claims that EPA views working level (WL or progeny) measurements as equally acceptable to radon gas (pCi/L) measurements. Radon gas measurements should always be preferred, especially when the measurement result will be used in mitigation decisions.

Since the actual radon gas measurements from the ZCES are available, they should be used in mitigation decisions, provided the measurements were obtained in accordance with the EPA Radon Measurement in Schools Protocol (EPA 420-R-92-014, July 1993). The Schools protocol allows for initial short-term measurements to be conducted in every ground contact room. Measurement results at or above 4 pCi/L (e.g., 4-10 pCi/L) should be verified with follow-up measurements which can be long-term or short-term. Long-term measurements (90-days+) give a more accurate estimate of the average annual radon level.

Making a good working level or progeny measurement is more difficult than making a radon gas measurement. Because of the uncertainties associated with progeny measurements, the state of New Jersey and the American Association of Radon Scientists and Technologists (AARST) do not recommend making mitigation decisions based on working level measurements. Working level (WL) measurements are mentioned very briefly in EPA documents. The main reason for their inclusion is that in the early years of EPA's radon program there were some devices being used in the market to measure working level (progeny). The use of WL devices has declined over time due to the difficulty and expense of making such measurements.

For the reasons above, EPA's recommendation is to base a mitigation decision on a gas measurement, which we consider a conservative and protective, as well as practical way to evaluate potential risk. More simply put, "no radon gas, no risk." Of course, there is rarely, if ever, "no" radon gas. Background concentrations of radon in outdoor air can vary from place to place and time of day. The available data suggest that the outdoor average is about 0.4 pCi/L, or 1/10th EPA's action level.

Radon health risk. To our knowledge, lung cancer is the only health effect from exposure to radon in air. There are no data to suggest that children are at greater risk from exposure to radon in air than are adults. Recent radon risk assessments confirm that the risk at relatively low levels of radon is significant. For this reason, EPA recommends that mitigation be considered at levels even below our action level of 4 pCi/L (and specifically between 2 and 4 pCi/L) for residential structures. As you know, the 2003 EPA risk assessment estimated 20,000 annual radon-related lung cancer deaths. It's important to remember that this estimate is based on exposure to 1.25 pCi/L, which is the average U.S. indoor radon level. It is for these reasons that the International Commission on Radiation Protection (ICRP) recommends that radon be reduced to a level as low as reasonably achievable (ALARA).

Mitigation. EPA's principal recommendation for mitigating radon levels in school buildings is to control the source, i.e., to minimize or prevent radon entry. The technique used most often and successfully is sub-slab or sub-membrane Active Soil Depressurization (ASD). From the Fallon report we reviewed, it appears that the existing ZCES ASD systems have not been adequately evaluated for their effectiveness.

A complete and thorough evaluation of the existing ASD systems should be conducted. The evaluation should identify needed upgrades to, or extensions of, the existing radon mitigation systems. Any upgrades or new systems should conform to EPA's guidance. We recommend that school ASD systems be operated continuously. For the school's slab-on-grade footprint not served by an existing ASD system, if measurement results warrant mitigation, additional diagnostics should be done to determine whether ASD can be employed. These evaluation/diagnostic activities should be conducted by a qualified professional with experience in large, low-rise, slab-on-grade/crawlspace school/commercial buildings. Evaluations and diagnostics can be conducted independent of weather conditions and when convenient.

EPA does not recommend filtration as a radon control measure; the use of High Efficiency Particle Air (HEPA) filtration devices is not recommended as a mitigation technique. While there is evidence that filtration can reduce progeny concentrations, many factors can impinge on the effectiveness of filtration in maintaining reduced progeny concentrations with an attendant reduction in radon dose.

Some of these complicating factors include: a potential increase in ultra fine particles available for progeny attachment and deposition in the lung; a potentially larger percentage of progeny as an unattached fraction available to be deposited in the lung; maintaining a consistent air volume setting; human interference with filtration device operation; uncertainties with filter loading and progeny reductions; and the frequency of radon progeny measurements needed to maintain the target progeny concentration.

Technical assistance. Further technical assistance may be available to assist you in your ZCES deliberations. Radon professionals at EPA and the State of Nevada are available to support you through letters like this, via conference calls, etc. Also, onsite technical assistance may be available through the Conference of Radiation Control Program Directors (CRCPD). For such a request you should contact Adrian Howe with the Nevada State Radon Program (775-687-7531, ahowe@health.nv.gov).

We acknowledge the good offices of the State of Nevada Radon Program in addressing this issue to date. Thank you for the opportunity of joining in the effort to assist the Douglas County School District in resolving this important public health issue.

Sincerely,

Phil Jalbert [signed]	Gene Fisher [signed]
Radon Team Leader	Health Physicist
202-343-9431	202-343-9418
jalbert.philip@epa.gov	fisher.eugene@epa.gov

cc:
Ms. Holly Luna, Director, Business Services, Douglas County School District
Ms. Carol Lark, Superintendent, Douglas County School District
Dr. Susan Conrath, MPH, PhD, U.S. Public Health Service, EPA
Mr. Bill Long, Director, EPA Center for Radon and Air Toxics, EPA
Mr. Adrian Howe, State of Nevada Radon Program
Ms. Louise Hill, EPA Region 9 Radon Coordinator
Ms. Kelly Krolicki
Mr. Greg Felton

APPENDIX B: EXAMPLE OF RADON MITIGATION SYSTEM INSPECTION FORM

New Subslab Depressurization System Inspection Form (Page 1 of 2)

Building Number: __________　　**Building Name: _________________________________**

Date: __________　　**Inspectors:**

____

General System Description

System Number: Number Suction Points:	Suction Point Locations	Room(s) System Fixes
Fan Make and Model	Fan Location Interior_____ Exterior_____ Attic_____ Roof_____	System Design Ext. (Type 1) ___ Int. w egress (Type 2) ___ Int. w/o egress (Type 3) ___
Performance Indicator Type	Performance Indicator Location	Performance Indicator Reading
Breaker/Panel Number	Switch Location	Electrical Tap Location
Comments		

Drawings/Notes

New Subslab Depressurization System Inspection Form (Page 2 of 2)

Component	**Specification**	**Findings**	**Comments**
Vent Pipe	4 in, PVC, SCH 40, White	**Pass Fail**	
	Fittings and connections appear to be airtight, properly joined/sealed	**Pass Fail**	
	10 ft. above grade, at least 12 in. above eave/roof and at least 10 ft. from any opening to conditioned space	**Pass Fail**	
	Vent exhaust cap present	**Pass Fail**	
	Fire collar/damper present if fire rated wall is penetrated	**Pass Fail** **Not Applicable**	
	Sealing around vent pipe penetrations through slab, wall and floor is intact	**Pass Fail**	
	Pipe is strapped at least every 6 ft. on horizontal runs and every 8 ft. on vertical runs	**Pass Fail**	
	All exterior fasteners are stainless steel, galvanized, or corrosion resistant	**Pass Fail**	
Performance Indicator	A performance indicator is present, visible, operating and accessible.	**Pass Fail**	
	Pressure tubing is sealed and intact	**Pass Fail**	
	Instructions on how to use the indicator are present and a contact phone number is provided	**Pass Fail**	
Mitigation Fan	Mounted in a vertical section of pipe and level	**Pass Fail**	
	Fan is **not** located in or below conditioned space	**True False**	
	Vacuum within manufacturers performance range	**Pass Fail**	
	Fan not vibrating	**Pass Fail**	
Does System Meet EPA/ASTM/FTC Standards	Any negative findings above circle, No	**Yes No**	

APPENDIX C: EXAMPLE OF SSD O&M INSPECTION FORM

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O&M Subslab Depressurization System Inspection Form

Building Number: __________ **Building Name:** ________________________________

Date: __________ **Inspectors:** ____________________________________

System Number: _______ **Fan Make/Model:** ____________________________

Item	P	F	NA	Comments	Corrected
Fan Cover					
Cover Screws					
Fan Operation				Replacement Fan: ________________	
Fan Boots					
Fan Mounting					
System Decals					
Vacuum Indicator				Reading: __________	
Vacuum Tubing					
Pipe					
Pipe/Wall/Slab Seals					
Pipe Clamps					
Clamp Anchors					
Roof Cap					
Flex					
Flex Connectors					
Switch Operation					
Conduit					
Conduit Clamps					
Electrical Tap Seal					
Roof Seal					

Comments:

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